Design of A Ballast Tank
For A Small Underwater Remotely Operated Vehicle (ROV)

by

Mohd Ubaidillah bin Mohd Kamal
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the requirement for the
Bachelor of Engineering (Hons)
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CERTIFIVATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

____

(Mr. Azman bin Zainuddin)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

January 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that that original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Mohd Ubaidillah bin Mohd Kamal

ABSTRACT

Underwater Remote Operated Vehicle is tethered marine robots that are widely used in oil and gas industry. Underwater vehicles such as ROVs operate while tethered to a surface ship, and must be able to surface and submerge, thus requiring dynamic buoyancy control. ROVs also require dynamic buoyancy control for its own stability and depth control. The dynamic buoyancy can be applied by using Ballast Tank.

This project works involves designing and analysis of Ballast Tank for small, lightweight, open frame and low cost underwater Remotely Operated Vehicle (ROV). This system should be 2 Degree of Freedom (DOF); Yaw and Heave. The analysis and calculation have be done to determine the required size of ballast tank, its' system, durability and the strength. The materials for Chassis and Ballast tank have been selected by considering the requirement.

The tank has been design with several considerations. The 3D-drawing, detail drawing, assembly drawing and analysis of the tank have been done by using CATIA software.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

DOF	- Degree of freedom
ROV	- Remotely Operated Vehicle
SST	- Stainless Steel
MBT	- Main ballast tank

CHAPTER 1
INTRODUCTION

1.1 Background Study

An ROV is a “robot” that is used for many underwater applications; underwater exploration & documentation, recoveries, inspections, search and rescue, trenching, cable burial and much more. ROV can solve some of the major maritime security issues today; Seaport / Port Security and Surveillance, Ship Inspections, Pipeline Inspections, Oil Rig Surveillance and Inspections, Docking Perimeter Inspections and Detections, Barge Inspections, Docked Cruise Ship Inspections and Tanker Security and Inspections

ROV are free swimming at the operator’s commands and in some instances programmed to swim in certain patterns or locations. However, ROV are always attached to a control center usually based above the surface. The ROV and control center are attached to each other by an “umbilical” cable (or tether). The “umbilical” provides the power and data uplink between the control center and ROV. All the operating commands and information collected by the ROV are sent back and forth to each other through the “umbilical” wiring. In some instances the “umbilical” is reinforced with strength enhancements for recoveries.

Most of available ROV in the market used 2 type of thrusters; horizontal thruster and vertical thruster. Overall of this project is to make a research about the application of ballast tank system in order to replace the vertical thruster. The application of ballast tank system was widely used on military submarines. Basically, there are two ways to submerge the submarine; dynamic diving and static diving. Dynamic diving use speed of the submarine in combination with the dive planes to force the submarine under water (similar to the way airplanes fly). Static diving submarines dive by changing the buoyancy of submarine itself by letting water into ballast tanks.

1.2 Problem Statement

The current and future underwater exploration is moving forwards deepwater. Human divers are restricted by this kind of hazardous, human unfriendly and extreme environment. In order to accomplish underwater tasks, the remotely operated underwater vehicle is the best choice.

But, underwater vehicles are liable to faults or failures during underwater missions. Thrusters are one of the most common and most important sources of faults. In all but the most trivial cases the existence of fault may lead to the cancellation of the mission. The implication of small faults could be very expensive and time consuming.

Usually ROV have a horizontal and vertical thruster system. Both system should enable direct control of motion in 4 Degree of Freedom (DOF); surge, sway, yaw and heave. But, it would be harder to control other motion in other directions (i.e. forward, backward and side-to-side) if the vertical thrusters are running continuously.

To overcome this problem, the application of ballast tank can be applied. The ballast tank can control the positive and negative buoyancy to create yaw and heave direction of ROV during underwater task.

1.3 Objective and Scope of Study

The objective of this project is to develop new design which is using ballast tank to replace the vertical thruster system.

Later on, after develop the design of ballast tank system and base on information gathering, the decision have to make whether to built the prototype of this system on ROV or not with several considerations such as cost limitation and time consuming.

During this project development, several factors have to be considered;

1. Cost limitation - Cheap to construct
    - Using low cost material that full fit the minimum requirement such as tensile stress, strength and capability to stand high pressure and high temperature.

2. Maneuverability
    - ROV can perform the input given by operator to make sure there is no mistake happen during the diving operation.

3. Ballast tank system performance
    - The location of the outlet, underside of the tank should provide a way for water to drain from the tank while it is filling with air and prevent the water from becoming trapped in the tank.
    - The outlet quantities, allows for quicker refilling of the tank with water while the tank is at the surface.

The scope of study will cover several aspects;

1. The concepts of ballast tank system.

CHAPTER 2
LITERATURE REVIEW AND/OR THEORY

2.1 Ballast Tank [1]

A **ballast tank** is a compartment within a boat or ship that holds water. A vessel may have a single ballast tank near its center or multiple ballast tanks typically on either side. A large vessel typically will have several ballast tanks including double bottom tanks, wing tanks as well as forepeak and aftpeak tanks. Adding ballast to a vessel lowers its center of gravity, and increases the draft of the vessel. Increase draft may be required for proper propeller immersion.

A ballast tank can be filled or emptied in order to adjust the amount of ballast force. Ships designed for carrying large amounts of cargo must take on **ballast water** for proper stability when traveling with light loads and discharge water when heavily laden with cargo. Small sailboats designed to be light weight for being pulled behind automobiles on trailers are often designed with ballast tanks that can be emptied when the boat is removed from the water.

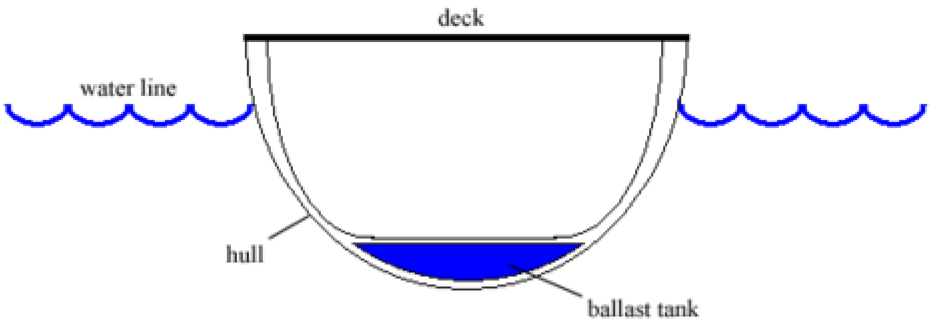


Figure 2.1 Ballast Tank in Ship

In submarines ballast tanks are used to allow the vessel to submerge, water being taken in to alter the vessels buoyancy and allow the submarine to dive. When the submarine surfaces, water is blown out from the tanks using compressed air, and the vessel becomes positively buoyant again, allowing it to rise to the surface. A submarine may have several types of ballast tank, the **main ballast tanks**, which are the main tanks used for diving and surfacing, and **trimming tanks**, which are used to adjust the submarine's attitude (its 'trim') both on the surface and when underwater.

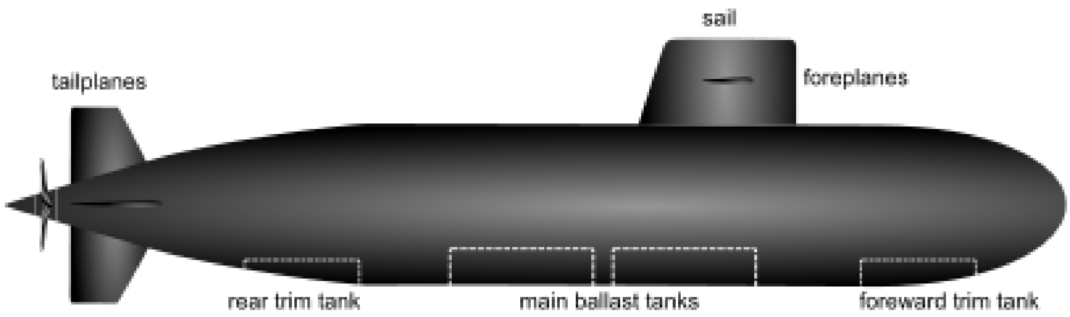


Figure 2.2 Ballast Tank in Submarine

2.2 Buoyancy Force [2]

It is common experience that an object feels lighter and weighs less in the liquid that it does in air. This can be demonstrated easily by weighing a heavy object in water by a waterproof spring scale. Also, objects made of wood or other light materials float on water. These and other observations suggest that a fluid exerts an upward force on a body immersed in it. This force that tends to lift the body is called the **buoyancy force** and is donated $F_{B.}$ [2]

The buoyancy force is caused by the increase of pressure on a fluid with depth. Consider, for example, a flat plate thickness *h* submerged in a liquid of density ρ_f parallel to the free surface, as shown in Figure 2.2. The area of the top (and also bottom) surface of the plate is A, and its distance to the free surface is *s*. The pressures at the top and bottom surface of the plate are $\rho_f gs$ and $\rho_f g(s+h)$, respectively.

Then the hydrostatic force $F_{top} = \rho_f gsA$ acts downward on the top surface, and the larger force $F_{bottom} = \rho_f g(s+h)A$ acts upward on the surface of the plate. The difference between these two forces is a net upward force, which is the *buoyant force,*

$$F_B = F_{\text{bottom}} - F_{\text{top}} = \rho_f g(s+h)A - \rho_f gsA = \rho_f ghA = \rho_f gV$$

Where $V = hA$ is the volume of the plate. But the relation $\rho_f gV$ is simply the weight of the liquid whose volume is equal to the volume of the plate. Thus, we conclude that *the buoyancy force acting on the plate is equal to the weight of the liquid displaced by the plate.*[1]

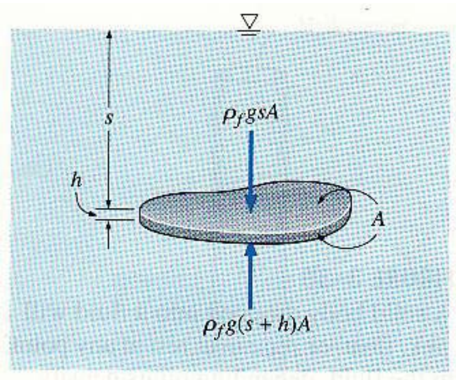


Figure 2.3 A plate of uniform thickness h submerged in a liquid parallel to the surface.

2.3 Archimedes's Law

Consider an arbitrarily shaped solid body submerged in a fluid at rest and compare it to a body of fluid of the same shape indicated by dotted at the same distance from the free surface, Figure 2.4.

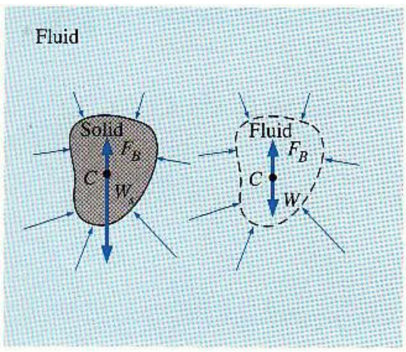


Figure 2.4
The buoyant for Fb acts upward through the centroid C of the displaced volume and equal in magnitude to the weight W of the displaced fluid, but is opposite in direction. For a solid of uniform density, its weight Ws also acts through centroid, but its magnitude is not necessarily equal to that of the fluid displace (here Ws>W thus Ws>Fb; this solid body would sink)

The buoyant force acting on these two bodies are the same since the pressure distributions, which depend only on depth, are the same at the boundaries of both. The imaginary fluid body is in static equilibrium, and thus the net force and net moment acting on it are zero. Therefore, the upward buoyant force must be equal to the weight of the imaginary fluid body whose volume is equal to the volume of the solid body. Further, the weight and the buoyant force must have the same line action to have a zero moment. This is known as **Archimedes' principle,** after the Greek mathematician Archimedes (287 – 212 BC), and is expressed as

> *The buoyancy force acting on a body immersed in a fluid is equal to the weight of the fluid displaced by the body, and it acts upward through the centroid of the displaced volume.* [2]

For *floating* bodies, the weight of the entire body must be equal to the buoyant force, which is the weight of the fluid whose volume is equal to the volume of the submerged portion of the floating body. That is,

$$F_B = W \rightarrow \rho_f g V_{sub} = \rho_{ave,\,body} g V_{total} \rightarrow \frac{V_{sub}}{V_{total}} = \frac{\rho_{ave,\,body}}{\rho_f}$$

Therefore, the submerged volume fraction of a floating body is equal to the ratio of the average density of the body to the density of the fluid. Note that when the density ration is equal to or greater then one, the following floating body becomes completely submerged. [2]

It follows from these discussions that a body immersed in a fluid

1. remains at rest at any point in the fluid when its density is equal to the density of the fluid
2. sink to the bottom when its density is greater than the density of the fluid
3. rises to the surface of the fluid and float when the density of the body is less than the density of the fluid.

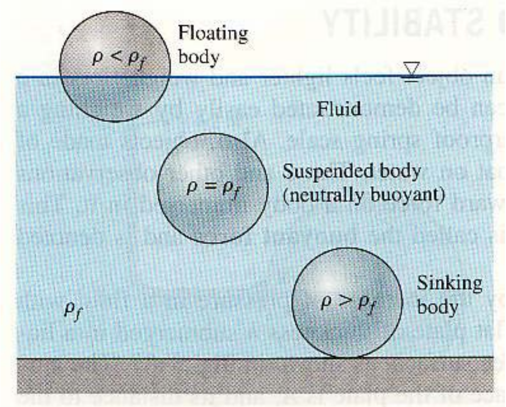


Figure 2.5
A solid body dropped into a fluid will sink, float, or remain at rest at any point in the fluid, depending on its density relative to the density of the fluid.

2.4 Static Diving [3]

The buoyancy of a submarine can be changed by letting water into the main ballast tanks (MBT). The MBT's can be located in three different ways:

(a) Inside the pressure hull,

(b) Outside the pressure hull as additional tanks, and

(c) In between the outer hull and the pressure hull.

Figure 2.6 shows the three possible configurations. Drawback of having the MBT inside the pressure hull is obvious: it takes up space that could otherwise be used for equipment, weapons or personnel. This MBT arrangement was used in the WW-I boats and other early submarines. The classical example of a boat with MBT's outside the pressure hull is the German Type VIIC but also American and Dutch submarines in WW-II used this design. Due to the location of the MTB's, they are called saddle tanks. Most modern military submarines use the space in-between the inner pressure hull and the outer hull as MBT.[3]

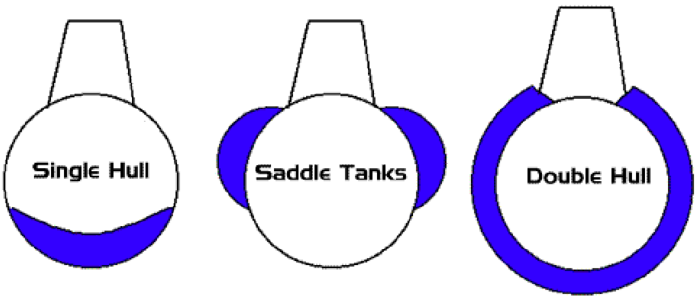


Figure 2.6 Different locations of the main ballast tank.

There are two different ways the MBT's can be emptied and filled. These methods will be referred to as the the western (USA, UK) method and the Russian method. Figure 2.8 depicts the both methods, the left hand side of the pictures shows the USA/US method, the right hand side the Russian method. When surfaced, the MBT are entirely filled with air and the main vent valves on top of the MBT are closed. In the USA/UK boats the flood opening at the bottom of the MBT always remains open. Water is prevented to enter the MBT because the air in the MBT is pressurized, at about 10 PSI. In the Russian boats, the bottom flood opening is closed with a valve, a so called Kingston. Because the Kingston prevents water entering, air in the MBT can be at approximately atmospheric pressure. To dive the boat, the vent valves on top of the ballast tanks are opened to let air escape the MBT. Because in the USA/UK boats the air is pressurized, the air roars out of the vents, resulting in a large spray of water, see Figure 2.7

Figure 2.7 An Ohio class submarine venting the forward ballast tanks.

In the Russian technology, the Kingstons at the bottom of the MBT also have additionally to be opened in order to let water enter the MBT. It is claimed that because the air in the USA/UK boats is pressurized (more gas in the MBT and larger friction in the vent valves) the Russian MBT is flooded more quickly.

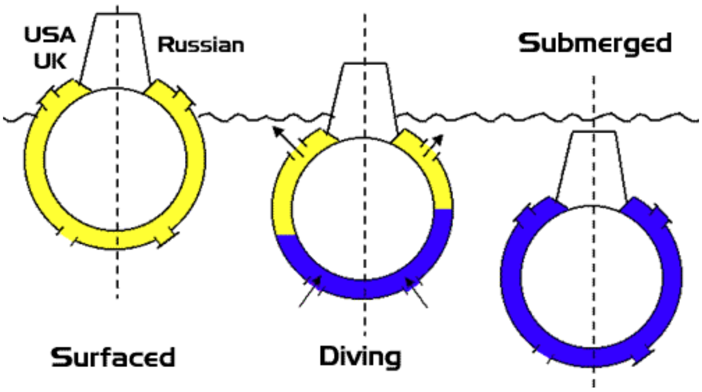


Figure 2.8 Flooding of the main ballast tanks.

To surface the boat, the water in the MBT's is forced out by pressurized air. When the boat is deeply submerged, the water is forced out using high pressure air to overcome the water pressure. Once the boat is near the surface, the blowing of the MBT's proceeds with low pressure air. Once at the surface, the Russian boats close the Kingston valve and then opens the main vent valve briefly to equalize the air pressure in the MBT with that of the atmosphere. In the USA/UK boats, the main vent valve remains shut to keep the air in the MBT under pressure. The pressure inside the tanks remains equal to that of the low pressure air system.

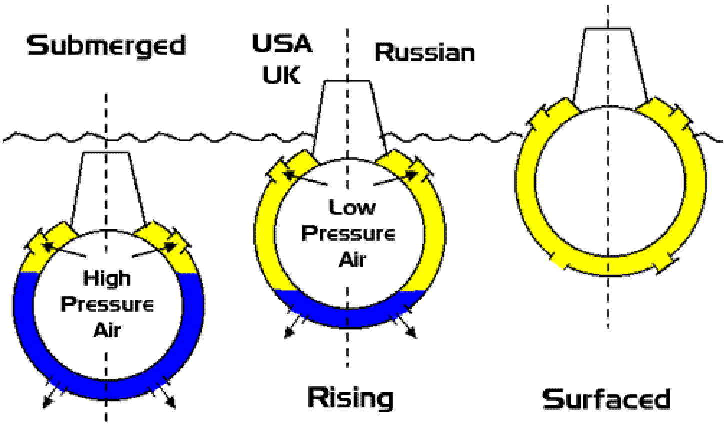


Figure 2.9 Blowing of the main ballast tanks.

2.4.1 Static Diving Technology[3]

In real submarine, MTB are filled by venting the air inside the air tanks and are emptied by blowing compressed air in to them. For model submarines a number of alternative methods are available. [3]

1. **Vented Ballast Tank[3]**

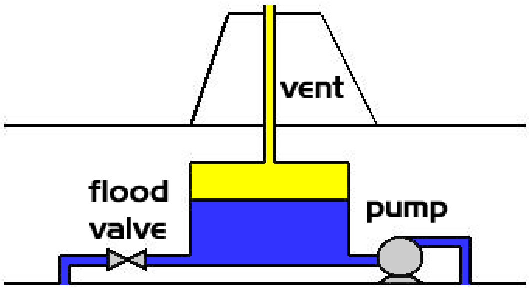


Figure 2.10 Vented Ballast Tank.

The vented tank (Figure 2.10) can be used to decrease the buoyancy of the boat from positive to slightly positive (decks awash). If the flood valve is opened, the air can escape through the vent and water fills the tank. The tank can be emptied by pumping water out of the tank while air is sucked back into the tank through the vent. Note that in order for this system to work, the top of the vent line must be above the water level. That is why the vented tank cannot be used to give the boat neutral or negative buoyancy. With a filled tank the boat can dive using the hydroplanes. Note that if a bi-directional pump is used, the flood valve is not needed. To prevent water getting in to the ballast tank when running submerged, the diameter of the vent line should be kept small.

2. Flexible Ballast Tank[3]

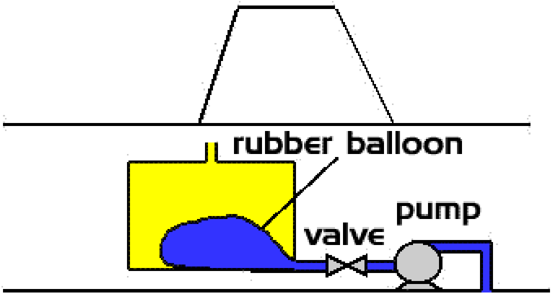


Figure 2.11 Flexible Ballast Tank.

The flexible tank (Figure 2.11) consists of a rubber balloon placed inside a rigid tank. To flood the tank, the valve is opened and water is pumped into the tank. The valve is closed to prevent water getting out once the tank is flooded. The air originally present in the rigid tank is vented into the pressure hull of the boat. This will lead to an increase of the pressure inside the hull. If the volume of the ballast tank is not to large compared to the air volume inside the pressure hull this is not a problem. Note that the inside of the submarine is usually packed with equipment so the air volume is certainly not equal to the hull volume.

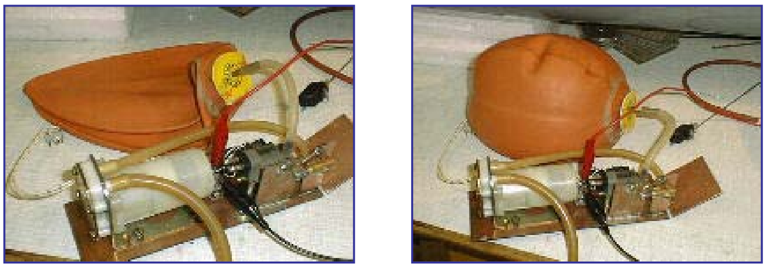


Figure 2.11a Flexible ballast tank, empty and full, by Wilhelm Sepo

3. Pressure Ballast Tank[3]

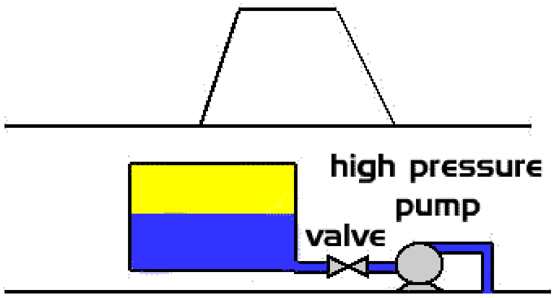


Figure 2.12 Pressure Ballast Tank.

The pressure ballast tank (Figure 2.12) consists of a sealed ballast tank capable of with standing a significant pressure increase (5 bars or so). To flood the tank, water is pumped into the tank with a high pressure water pump; because the air in the ballast tank cannot escape the air is compressed. To empty the tank, the water pump pumps the water out of the tanks again. Because the pressure build-up inside the ballast tank it can never be completely filled. Assuming a maximum pressure of 5 bars inside the tank, about 80 percent of the volume of the ballast tank can be used.

4. Piston ballast tank[3]

The piston ballast tank (Figure 2.13) consist cylinder and a movable piston, just like a giant syringe. The piston can be moved with a thread, a cogwheel and a small motor. The outer end of the cylinder is directly connected to the surrounding water. In the piston ballast tank no air is present. Just like the flexible tank the pressure inside the boat increased if the piston tank is filled with water. If the position of the cylinder is measured, for example with a linear potentiometer connected to the thread, the buoyancy of the boat can very accurately be adjusted. Due to the large stroke of the piston, these types of ballast tanks are mostly fitted horizontally, like in Figure 2.11. This means that during filling of the tank with water the axial center of gravity of the boat is affected. For example if the boat is balanced to run horizontally with a full ballast tank, the angle of the boat is no longer zero with an empty tank. This drawback can be overcome by using two piston tanks in the aft and bow section of the boat.

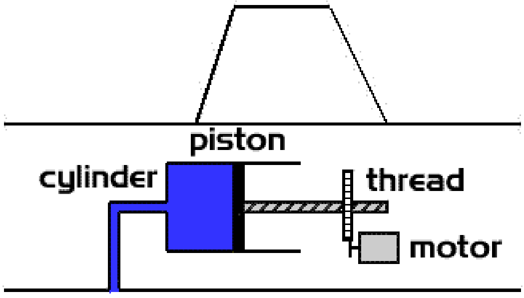


Figure 2.13 Piston Ballast Tank.

The piston tank can be purchased from Norbert Bruggen, see Figure 2.12a. In this system, a small electric motor drives the piston in the plastic cylinder. Two micro switches interrupt the current to the motor if the piston is in either fully retracted or fully deployed.

Figure 2.13a Piston Ballast Tank by Norbert Bruggen

5. Membrane ballast tank[3]

The membrane ballast tank (Figure 2.14) is a simplified version of the piston tank. It consists of a rigid disk that can be moved up and down with a thread connected to a motor, just like the piston tank. The disk is connected to the cylinder via a flexible rubber membrane. When the disk is retraced, water is allowed into the boat. A nice aspect of the membrane ballast tank is that the water tight sealing is very easy. As long as the rubber membrane is properly attached to both disk and tank, leaking is not possible. In a piston tanks the sealing between the piston and the cylinder is quite critical. Drawback of the membrane tank is that the stroke of the piston is not very large so the change in buoyancy of the submarine is not very large. To make optimal use of the membrane tank, the diameter of the cylinder should be rather large compared to its height. The system is however ideal for small, or micro, model submarines.

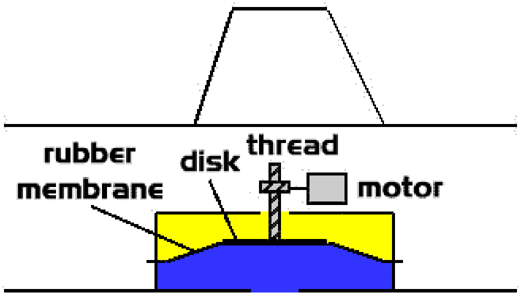


Figure 2.14 Membrane Ballast Tank

6. Bellow ballast tank[3]

The bellow ballast tank (Figure 2.15) is a variation on the membrane ballast tank. Instead of a flat membrane a rubber bellow is used. This has the advantage that the stroke of the disk is increased so that more water can be taken into the boat. Rubber bellows of sufficient diameter, 5 to 10 cm or so, can be found in car parts shops. In cars they are for example used to seal off moving parts of the steering equipment. Under pressure, the zig-zag wall of the membrane may pop out, resulting in a sudden increase of the ballast volume (and sinking of the sub). To prevent this, it is recommended to fit the bellow inside a cylinder.

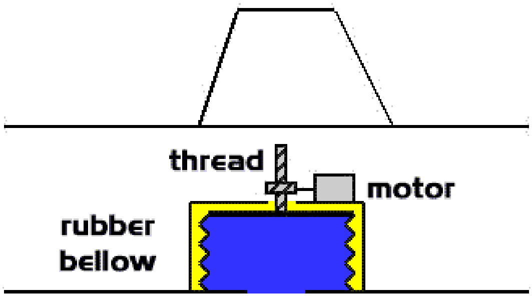


Figure 2.15 Bellow Ballast Tank.

7. Gas operated ballast tank[3]

The liquid gas system (Figure 2.16) consists of a storage cylinder with pressurized gas, a ballast tank and two valves. This system resembles the ballast system of a real submarine very closely. To flood the tank, the valve in the vent line is opened and water is allowed into the tank via the opening in the bottom. If the required volume of water is taken in, the vent valve is closed. The tank can be emptied by forcing pressurized gas into the tank by opening the blow valve. If we want the model boat to be able to blow the ballast tank a number of times, the stored amount of gas should be sufficient. Carbon dioxide (CO_2) is an option because cylinders with this gas are relatively cheap and readily available from Paint ball shops. In paint ball, cylinders of 50 to 500 gram are commonly used. If CO_2 cylinders are used a reduction valve to bring back the pressure to about 2-3 bar is necessary.

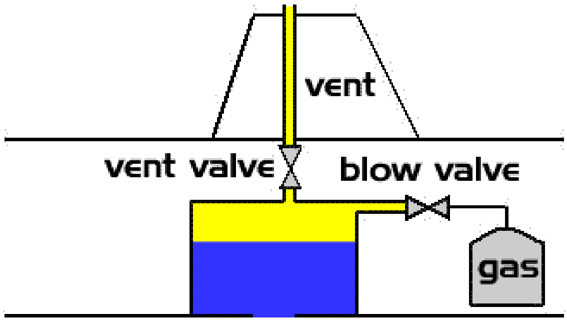


Figure 2.16 Gas Operated Ballast Tank.

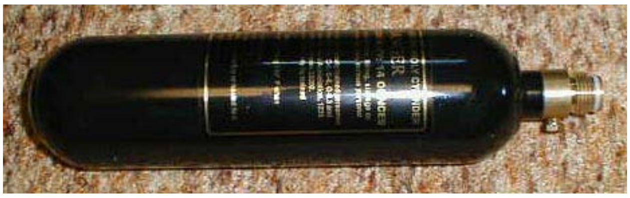


Figure 2.17 A CO_2 cylinder (14oz).

An interesting alternative to CO_2 is the use liquefied gas, for example canisters used for air brushing (propane), canisters used to clean photo equipment or electronics called 'dust-off' (dimethylether/tetrafluorethane) or propell (tetrafluorethane). Because these gases are stored as a liquid, the amount of gas that can be stored is quite large. It is also very easy to refill the gas tank in the submarine form a larger stock cylinder. With CO_2 do it your self refilling is not that easy so that spare cylinders have to be taken to the lake. An additional advantage of liquid gas is that the pressure inside the storage vessel is about 3 to 4 bar so there is no need for a pressure reduction vale. A very serious draw back of these gases is its flammability. If the storage vessel leaks an explosive mixture may form inside the pressure hull of the boat. The sparks of the electric motor are sufficient to detonate it! The only real safe liquid gas is tetrafluorethane. The dust-off product contains about 20 percent of the flammable dimethylether and is potentially hazardous.

In the gas ballast system the electric valves used in the gas line (the blow valves) can be standard solenoid valves used in laboratory equipment. To prevent draining of the batteries, valves that are normally closed should be used. Using CO2 with a pressure reduction valve or liquid gas, the pressure at which they remain closed should be about 5 bars.

The vent valves that let air out of the ballast tank to submerge the boat are different. The pressure difference between the air in the tank and that of the ambient air is only a couple of cm water. Therefore the opening of the vent valve should be quite large to let our air at a sufficient flow rate to get a realistic dive. Because the pressure difference is also quite small when the vent valve is closed, and thus the boat is submerged, we can make these valves ourselves. Note that many of the above-mentioned solenoid valves have an opening of less than 1 mm and do usually not like water getting in to it, these types of valves are not very suited.

8. Compressed air ballast tank[3]

The ballast tank system that uses compressed air is identical the one used in real submarines. This system is similar to the gas operated ballast tank but in this case the gas bottle is replaced by a cylinder that is filled with a compressor. These compressors are capable of compressing air to about 6 to 8 bars. These pressures are high enough to be careful with the storage cylinder. The pressure is however relatively low pressure if you consider the amount of gas that can be stored. If the compressed air cylinder is half the size of the MBT, we can only blow the MBT two to three times. This is not much compared to CO2 or liquid gas systems. In general, boats with on board air compressors refill the air supply each time they run on the surface after a dive.

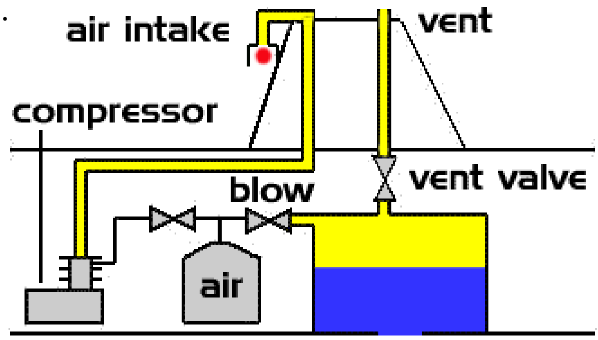


Figure 2.18 Compressed Air Ballast Tank.

2.5 Application of Ballast Tank in ROV

1) During "2003 ROV competition design specification and mission challenger", a group of student from Massachusetts Institute of Technology have come out with the application of the ballast tank to overcome the power constraint on vertical thruster and difficulty to control other motion (i.e. forward, backward and side-to-side) if the vertical thruster are running continuously during the rescue mission of RUSTI, an ROV that was lost in the exploration of the Titanic on 2001.[4]

2) SEAEYE ROV used by SapuraCrest Petroleum Berhad [5]

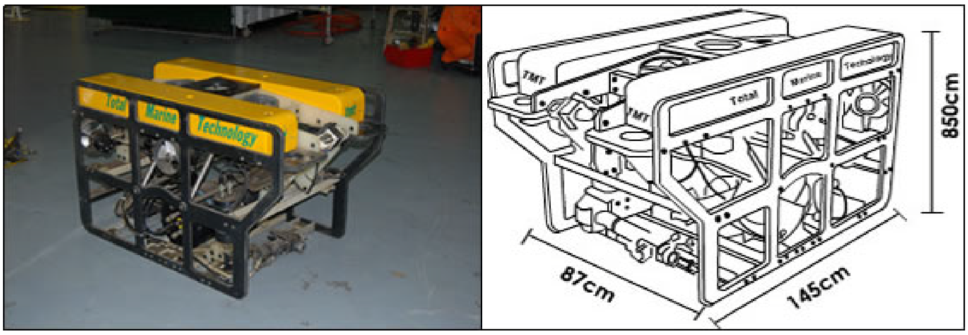


Figure 2.19a SEAEYE ROV used by SapuraCrest Petroleum

SEAEYE ROV used by SapuraCrest Petroleum Berhad which has two block of closed cell polyurethane foam either side of the vertical thruster along the entire length of the vehicle to give the buoyancy forve.[5]

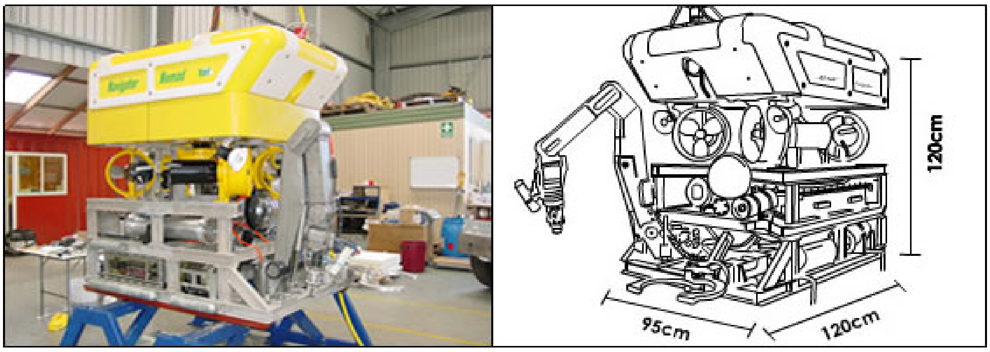


Figure 2.19b NAVIGATOR ROV used by SapuraCrest Petroleum

Another ROV used by SapuraCrest Petroleum Berhad, NAVIGATOR ROV, which has a Ballast Tank on the top of ROV.

2.6 Drag Force [7]

When any body moves through a fluid, an interaction between the body and the fluid occurs: this effect can be described in terms of the forces at the fluids-body interface. This can be describe in term of the stresses – wall shear stresses, τ_w due to viscous effects and normal stresses due to the pressure, *p*. Typical shear and pressure distributions are shown in Figs. 2.20a and 2.20b. Both τ_w and *p* vary in magnitude and direction along the surface.

The resultant force in the direction of the upstream velocity is termed the *drag, D,* and the resultant force normal to the upstream velocity is termed the *lift, L,* as is indicated in Fig.2.20c.

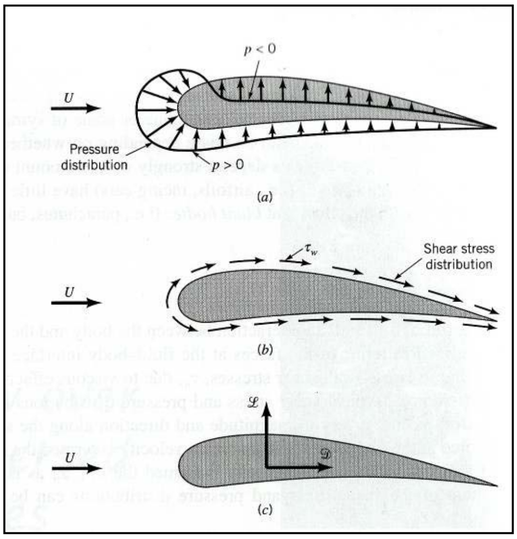


Figure 2.20
Forces from the surrounding fluid on the 2D object: a) pressure force, b) viscous force, c) resultant force (lift and drag) [7]

Drag coefficient information for very wide range of the objects is available in the literature. Some of this information is given in **Appendices** (Figures A1, A2 and A3) for a variety of two and three-dimensional, natural and man-made objects. A drag coefficient of unity is equivalent to the drag produced by the dynamic pressure acting on the area of size A.

The formula to calculate the drag force is: [8]

$$F_D = 0.5\rho C_D A_D V_O^2$$

Where;

F_D = Drag Force

ρ = density of water

C_D = drag coefficient

A_D = the projected area normal to the flow direction

V_O = the design speed of the vehicle

CHAPTER 3
METHODOLOGY / PROJECT WORK

3.1 Design Methodology

In ensuring this project can be executed smoothly, it has been divided into 2 major phases, shown in Figure 3.1

- Pre-design phase
    1. Preliminary Study & Identification of Problem
    2. Literature Review
- Design phase
    1. Design Stage & Selection Justification
    2. Design Simulation and Analysis
    3. Submission

Preliminary & Identification	**Literature Review**	**Design Stage & Selection Justification**	**Design Analysis**	**Submission**
1. Problem Identification 2. Objective Identification 3. Project scope 4. Methodology	1. Background Theory 2. Review Current Research 3. Project Identification	1. Calculation of Ballast System 2. Consideration Factors. 3. Propulsion	1. Analysis of the design. 2. Redesign	1. Design review 2. Final presentation 3. Dissertation

Figure 3.1 Summary of project work

3.1.1 Pre-design Phase

The project was started with defining the problem, identifying the needs, understanding and revamp knowledge about the application of ballast tank in submarine. This phase was conducted in the 1st semester.

3.1.2 Design Stage

This project will continue the Design Phase (second phase) during the 2nd semester. Based on the research during the 1st phase, several specifications in designing and developing the ballast tank have been considered to make sure this system give the better performance. The specification including;

1. Capital cost and running cost
2. Performance of Ballast system
3. Durability and strength
4. Size and weight
5. Safety

3.1.3 Tools/Equipment Used

In the design phase, CATIA software has been used to make a design because it is user friendly and capable to design in 3D image. Any changes and redesign task can be done easily by using this software.

This software also provides the Finite Element Analysis which is used for simulation and stress distribution analysis.

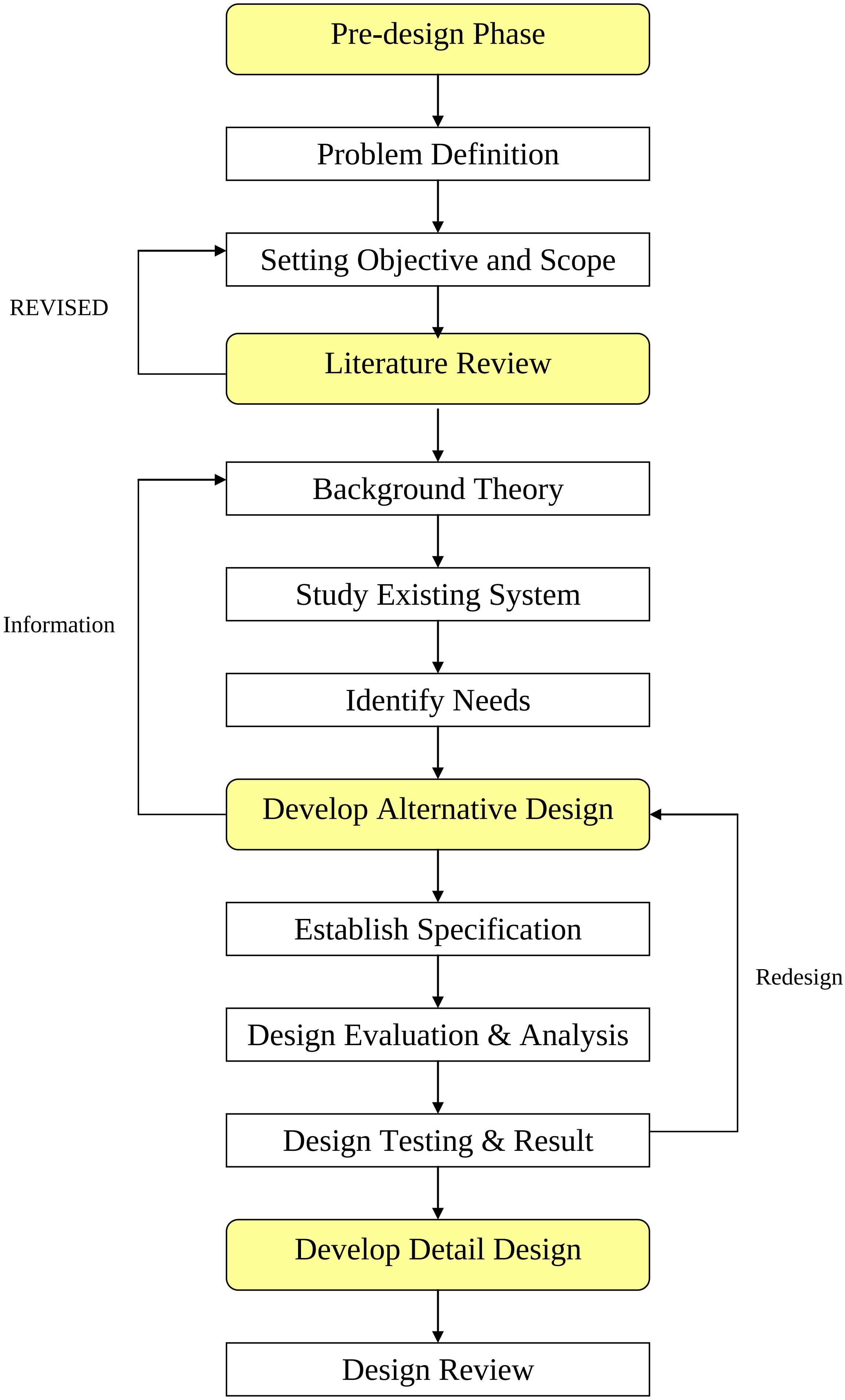


Figure 3.2 Design Project Works Process Flow

CHAPTER 4
RESULT AND DISCUSSION

4.1 Project Design Criteria and Limitation

The specification about the ROV was taken from a project done by Mr. Ahmad Syukri bin Shafie, Final Year Project Thesis, *Design of Underwater Remotely Operated Vehicle for Offshore Oil and Gas Industry*. In the report, the specification and the limitation of the ROV have been concluded as shown below.[8]

Mission	Survey and inspection
Water Depth Capability	Maximum depth of 30m
Power source	Electric (battery)
Weight	Maximum weight of 10 kg
Control method	Umbilical (wire/cable)
Top speed (horizontal)	2m/s
Size	0.5m L x 0.45 m H x 0.3 m W
Frame/chassis	Open Frame

Table 4.1 Criteria and Limitation of the ROV

The following table shows the part for Ballast Tank System.

No	Part	Function
1	Open Frame Chassis	Main structure of the ROV. Provide specific place for Ballast Tank to make sure the stability of ROV.
2	Ballast Tank	Provide enough needed Buoyancy Force.
3	Pneumatic System	Control the air volume in the Ballast Tank. Including the air supply, control valve and tubing.

Table 4.2 Major parts for Ballast Tank design.

4.2 Chassis Design

The frame is the main structure of the ROV. The frame will provide space for the important equipment of ROV such as main compartment which contain electrical and electronic devices, thruster and other additional equipment depend on the task design. For example if the ROV was design to take a sample of soil undersea, the ROV design should have robotic arm or other application that possible to take the soil sample.

4.2.1 Design Consideration

From the Criteria and Limitation of ROV above, the best design chassis that have been conclude is the open frame chassis. The open frame chassis meet all the following consideration:

1. Lighter in weight to make sure total weight of ROV not exceed the setting weight.
2. Enough space to supply what is needed
3. Provide low drag force
4. Provide stability
5. Inexpensive, available and easy to fabricate material with strong strength.

4.2.2 Layout Drawing for Chassis

Figure 4.1, show the design suggested by Syukri with dimension 0.5m long by 0.45 m high by 0.3 m wide.

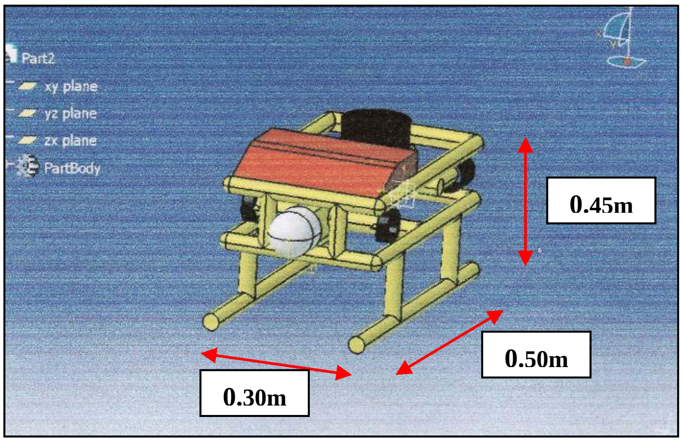


Figure 4.1 Suggested design and dimension by Mr. Ahmad Syukri

After consider several factors, the chassis has been redesign. The main size was still the same as suggested but the height has been reduced in order to decrease the center of gravity. The base area also has been increased. This change is very important to make sure the stability of the ROV since the installation of the Ballast Tank is on the top of the chassis. (See Appendices for detail drawing and assembly drawing)

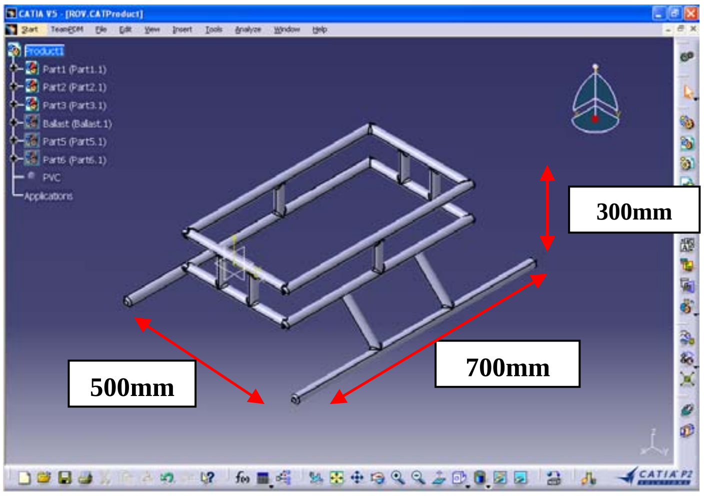


Figure 4.2 New chassis dimension design

4.3 Ballast Tank Design

The ballast tank is the most important part in this project. The major function of this tank is to provide enough buoyancy force needed by the ROV during surface and submerge mission by control the water inside the tank.

4.3.1 Ballast tank design consideration

The design of the Ballast Tank should incorporate with the following consideration:

1. Dimension of the tank should have enough volume to generate requirement buoyancy force, F_B.
2. The design shape of the tank influenced by the limitation space of ROV and should provide the minimum amount of hydrodynamic drag.
3. Simple and easy to fabricated

4.3.2 Options for Ballast System design

From the literature review, the alternative method of ballast tank for ROV prototype can be concluded into 3 major system; pump & valve, motor & piston and compressed air. Below was some comparison between the options.

Criteria	**Option 1** **Pump & Valve**	**Option 2** **Motor & Piston**	**Option 3** **Compressed Air**
Design complexity	Complex	Complex	Simple
Weight	Heavy	Heavy	Light
Cost	High	High	Average

Table 4.3 Summary of each ballast tank system

4.3.3 Volume Requirement

The volume of the tank should give enough buoyancy force to support the maximum weight of the ROV that has been early setup (not exceed 10 kg). The requirement volume can be determined using Archimedes's Principle that has been discussed before.

$$\boxed{F_B = \rho_f g V}$$

$$\boxed{W = mg = \rho_f g V}$$

F_B	=	buoyant force
ρ_f	=	fluid density
g	=	standard acceleration of gravity
V	=	Volume of the body
W	=	Weight of the fluid whose volume is equal to the volume of the submerge portion

$W = mg = \rho_f g V$

$(10kg)(9.81ms^{-2}) = (1025kg/m^3)(9.81ms^{-2})(V)$

$V \quad = 0.0097560\ m^3$
$\approx 0.01\ m^3$

Base on the calculation, the minimum volume to support 10kg weight of ROV is $0.0097560\ m^3 \approx 0.01\ m^3$. In the calculation, the density of the brine water, $1025kg/m^3$ has been used. Below was some analysis considered different of air volume in Ballast Tank with different density of water, either fresh water or brine water. The density for the fresh water is $1000\ kg/m^3$ and then density for the brine water (sea water) is $1025\ kg/m^3$.The analysis was done by using Microsoft Excel software.

Fresh water (ρ = 1000 kg/m^3)

Air volume, m^3	F_b, $kgms^{-2}$	Mass Supported, kg
0	0.0	0.0
0.005	49.1	5.0
0.009	88.3	9.0
0.01	98.1	10.0
0.0149	146.2	14.9
0.1	981.0	100.0
1	9810.0	1000.0
5	49050.0	5000.0
10	98100.0	10000.0
15	147150.0	15000.0
20	196200.0	20000.0

Table 4.4a Buoyancy force for different air volume in fresh water

Brine water (ρ = 1025 kg/m^3)

Air volume, m^3	F_b, $kgms^{-2}$	Mass Supported, kg
0	0.0	0.0
0.005	50.3	5.1
0.009	90.5	9.2
0.01	100.6	10.3
0.0149	149.8	15.3
0.1	1005.5	102.5
1	10055.3	1025.0
5	50276.3	5125.0
10	100552.5	10250.0
15	150828.8	15375.0
20	201105.0	20500.0

Table 4.4b Buoyancy force for different air volume in brine water

4.3.4 Layout Drawing of Ballast Tank

The shape and the dimension of the Ballast Tank have been designed. The dimensions should provide the requirement volume needed to generate the minimum buoyancy force. (See Appendices for detail drawing and assembly drawing)

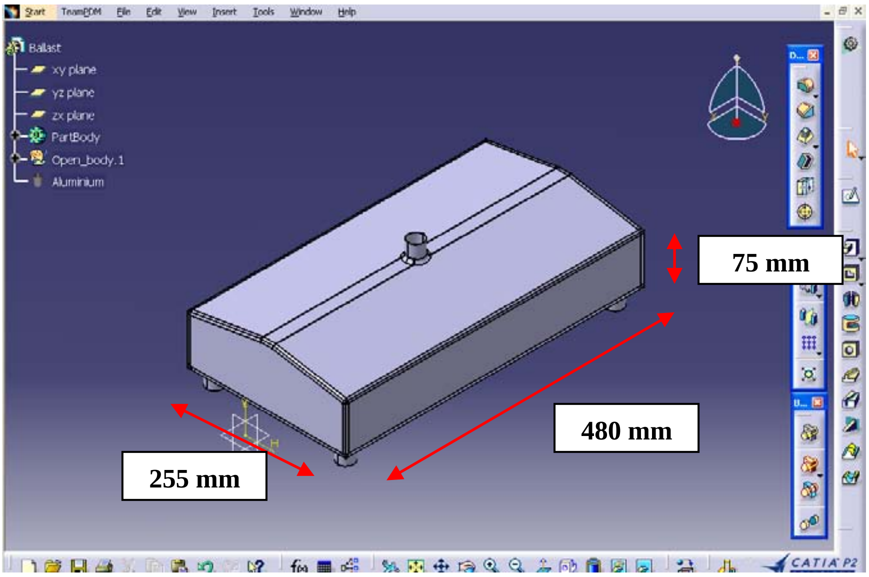
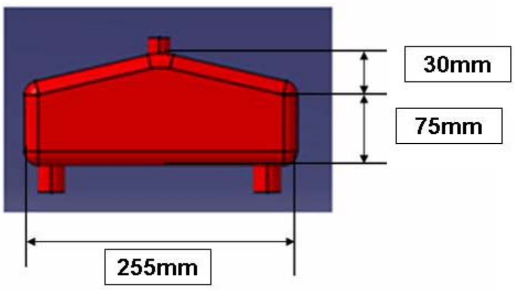
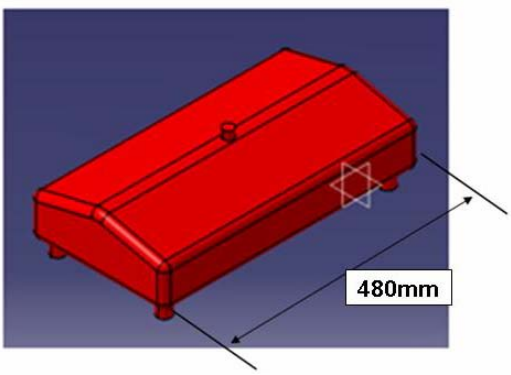


Figure 4.3 Ballast Tank

Calculation of buoyancy force using the design dimension and volume.





Cross sectional area

$A = (255\text{mm} \times 75\text{mm}) + (0.5 \times 255\text{mm} \times 30\text{mm})$

$A = 22950 \text{ mm}^2$

$\approx 0.02295 \text{ m}^2$

$V = 22950 \text{ mm}^2 \times 480 \text{ mm}$

$V = 11016000 \text{ mm}^3$

$V \approx 0.01 \text{ m}^3$

$F_B = \rho_f g V$

$F_B = (1025 \text{ kg/m}^3)(9.81\text{ms}^{-2})(0.01 \text{ m}^3)$

$F_B = 100.5525 \text{ kgms}^{-2} = W$

$m = 100.5525 \text{ kgms}^{-2} / 9.81\text{ms}^{-2}$

$m = 10.25\text{kg}$

The dimension of the ballast tank is approximately 480 mm long by 255 mm wide by 105 mm high, which displaces about 10.3kg of water when filled with air and will generated enough buoyancy force to surface the ROV. Underside of the tank, there were 4 outlets, near each corner, which provide a way for water to drain and prevent the water becoming trapped at each corner. It also allow the quicker refilling of the tank when submerge.

The tank is flat to keep the height of ROV to a minimum and give a space for others equipment such as main compartment (contain electrical devices) and horizontal thruster. The tank has a peaked design to provide more clearance along the side and decrease the hydrodynamic force during surface.

4.4 Installation of Ballast Tank

For the installation of the Ballast Tank into the chassis, the brackets will be used. The shape of the brackets followed the shape of the tank and it will have 2 part; above part and bottom part. Both of them will assemble by using a screw. The material of this bracket is same as the tank material, which is aluminum. (See Appendices for detail drawing and assembly drawing)

4.4.1 Layout Drawing for Brackets

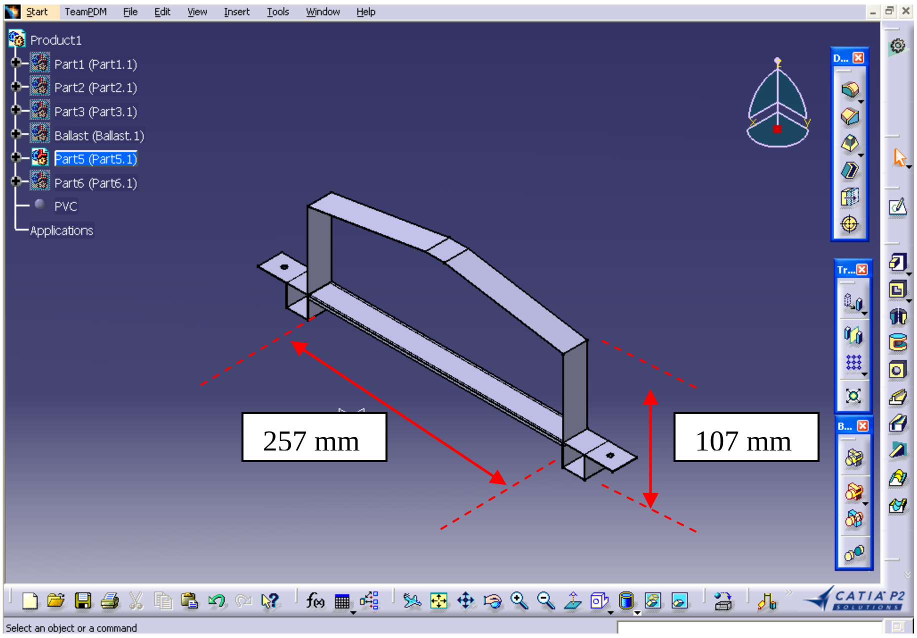


Figure 4.4 Installation bracket

4.5 Placement of Ballast Tank into ROV

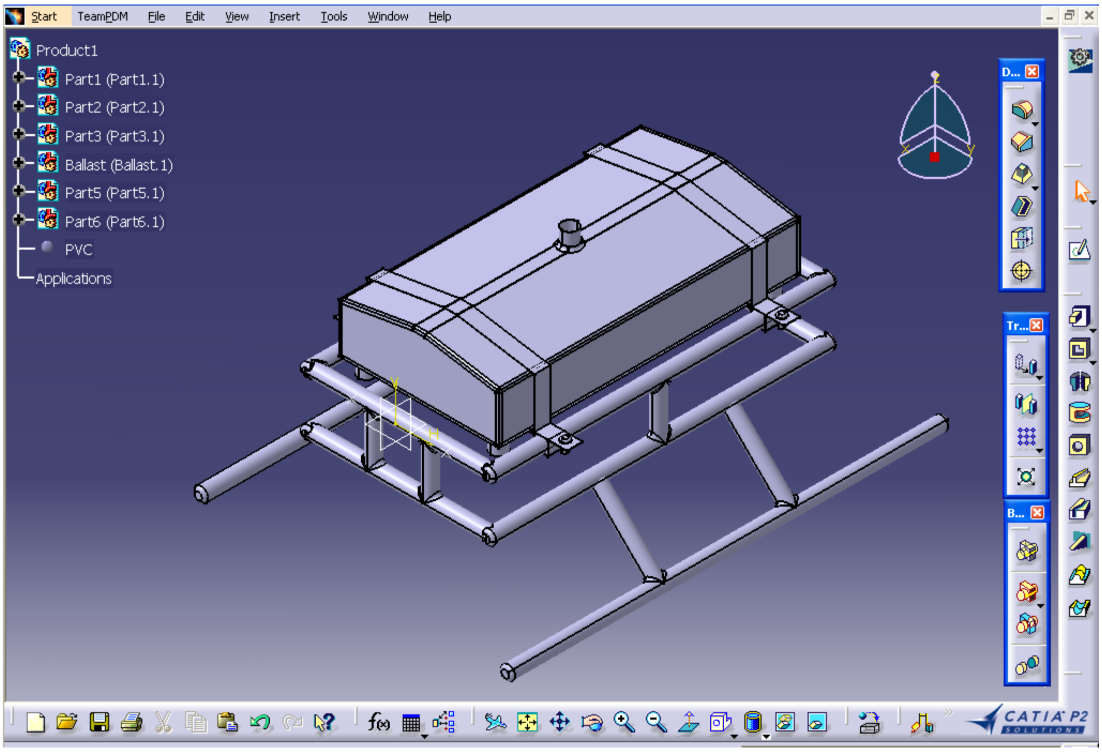


Figure 4.5a, 4.5b Placement of the Ballast Tank on the top of ROV

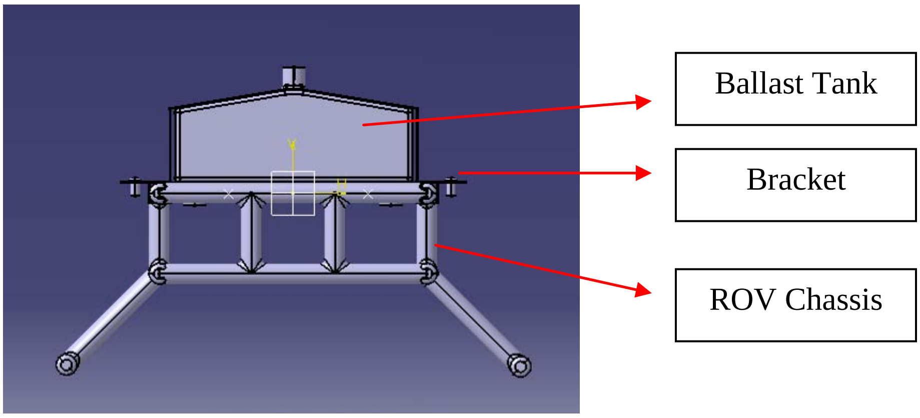


Figure 4.5b

The placement of the Ballast Tank on the top of ROV help ROV to aligned vertically stable. The placement also give a space for others equipment such as main compartment (contain electrical devices) and horizontal thruster.

4.6 Material Selection for Ballast Tank

The selection of the material should meet several requirements;

1. natural corrosion resistance
2. strong and lighter in weight
3. available and easy to fabricate
4. inexpensive

4.6.1 Options for material

Within the different metal types, metallurgists have developed alloys with complete ranges of performance from super high strength to soft. There are many specialty and exotic metal materials available that provide unique and useful properties. Standard for specific application abound. Nevertheless, the majority of products use quite ordinary materials from four groups: carbon steel, stainless steel, aluminum and cooper alloys.

Carbon Steel [6]

Carbon steel are inexpensive and strong, but are relatively heavy. Differences in molecular interaction of the iron and carbon atoms under various heating and cooling conditions give the wide range of properties attainable in these important materials. Although machinable, their strength and hardness means that fabrication methods can be slows. Free – machining types are preferred. Carbon steel is available in different stock sizes and shapes of sheet, bar, and plate. For most mechanical design, common types such as AISI 1018 are perfectly adequate. Since carbon steels rust when exposed to air, they are usually plated, painted or otherwise protected from corrosion in the final product. Springs, shafts, mechanism components, stampings, and fasteners are commonly made from carbon steel.

Stainless Steel [6]

Stainless steel, also known as SST, are alloys of iron, chromium, and nickel that have far superior resistance to rusting than ordinary steel. There are three basic groups stainless steel: austenite, martensitic, and ferritic.

Most common are the austenitic stainless steels, most of which have 300 series designations (e.g., 303, 316). Many of these are often simply called 18-8 stainless steels, referring to the percentage of chromium and nickel, respectively, in their composition. Austenitic 300 series stainless steels are generally not strong as 400 series or ordinary carbon steel. They are difficult to machine compared with many steels. Free-machining types, the most common are type 303, are available and improve machinability considerably. The 300 series stainless steels offer the best corrosion resistance among ferrous metals. Because of their corrosion resistance, they are often selected over carbon steel in high-temperature applications. They cannot be hardened with any type of heat treating, but are work hardened successfully fir high strength applications such as springs. Generally, 300 series stainless steel are nonmagnetic, but they become magnetic when work hardened.

Martensitic stainless steels, most of which have 400 series designations (e.g., 416, 440) are useful for their high strength and hardenability. Martensitic 400 series stainless steels are typically stronger than 300 series, but are less corrosion resistant. They are heat hardenable, giving them a good combination of very strength and resistance to rust. They are difficult to machine, especially in the hardened state, and usually must be ground rather than cut. They are often used in high-performance, corrosion-resistant fasteners such as clip rings and spring pins, but also in flatware and kitchen utensils. The 400 series stainless steel is magnetic. Ferritic stainless steel contains no nickel. They are used for drawn and formed parts because of their good ductility.

Aluminum [6]

Aluminum is generally not as strong as steels, but is significantly lighter in weight. In mild environments, it has a natural resistance to corrosion because the oxide formed on the surface protects the remaining metal from further oxidation. In aggressive environment, additional protections such as painting or anodizing are necessary. Most aluminum is quite easy to fabricate by forming and machining, particularly compared with carbon steel and stainless steel. It has poor bearing and friction properties. Aluminum has marked tendency to gall when sliding against it self or other metals. Therefore, it should rarely be used for sliding mechanism components. On the other hand, because it is easy to fabricate, inexpensive, lightweight, and strong, it is often ideal for static structural components such as brackets and housings.

Copper and copper alloy [6]

Copper and its alloys are important for some of their unique characteristic. These metals, especially pure copper, are excellent conductors of both heat and electricity. In many ordinary environments they exhibit excellent resistance to corrosion. Finally, they have excellent low friction and wear characteristics.

Although strong, they are not as strong as typical carbon steels, yet they are heavier. Their strength would be adequate for many structural parts, but their relatively high cost means that aluminum or steels are used instead for these applications. They are easier to machine than common steels.

For mechanical components, the most important of the copper alloys are brass and bronze. They are used in mechanical devices primarily because of their outstanding friction and wear characteristics. This makes them ideal for bearings and other sliding mechanism components.

Brass is an alloy of copper and zinc. Bronze is the term usually used for alloys of coppers and tin, although these are also often processed by sintering to make bearings. Lubricating fluids can be impregnated into these sintered materials making the bearings self-lubricating. Aluminum bronze is, as the name suggests, an alloy of copper and aluminum. It is somewhat harder and stronger than other copper alloys.

Criteria	**Option 1** **Carbon Steel**	**Option 2** **Stainless Steels**	**Option 3** **Aluminum**
Corrosion resistance	Poor	High	High
Weight	Heavy	Heavy	Lightweight
Fabrication difficulty	Easy to machine	Difficult to machine	Easy to machine
Price	Inexpensive	Expensive	Average

Table 4.5 Summary of material selection for Ballast Tank

Option 3, aluminum is chosen because it meets all the criteria.

4.7 Final Design Justification of Ballast Tank

The final design for the ballast tank is an aluminum tank approximately 480 mm long by 255 mm wide by 105 mm high, which displaces about 10.3 kg of water when filled with air. The tank has a peaked design to provide more clearance along the side and decrease the hydrodynamic force during surface.

On the underside of the tank, there are four outlets, one near each corner, which provide a way for water to drain ,prevent the water from becoming trapped in any corner of the tank and allows for quicker refilling of the tank with water when submerge. Each outlet is approximately 127mm in diameter.

The suggestion thickness of the sheet stock used is 3.175mm (1/8 inch) which is standard thickness available in market. The thickness chooses to make sure the minimum weight of the tank and the tank is not a pressure vessel type.

4.8 Simulation and Analysis

4.8.1 Free Body Diagram

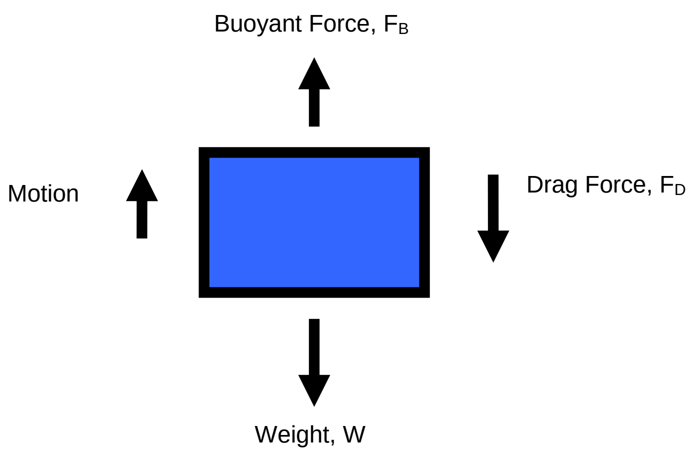


Figure 4.6 Free Body Diagram

4.8.2 Finite Element Analysis

The finite element method is a numerical procedure that can be used to obtain solutions to a large class of engineering problems involving stress analysis, heat transfer, electromagnetism, and fluid flow. There are many general-purposes finite element software that available in market such as ANSYS and CATIA. This project used CATIA software to analysis the stress concentration on the tank. Below shown one of the stress concentration analysis done using CATIA software.

<u>Analysis1</u>

Properties;

Material	Young Modulus	Poisson Ratio
Aluminium.1.1 : Alloy 1100-H14(99% Al)	7e+010N_m2	0.346

Boundary Condition

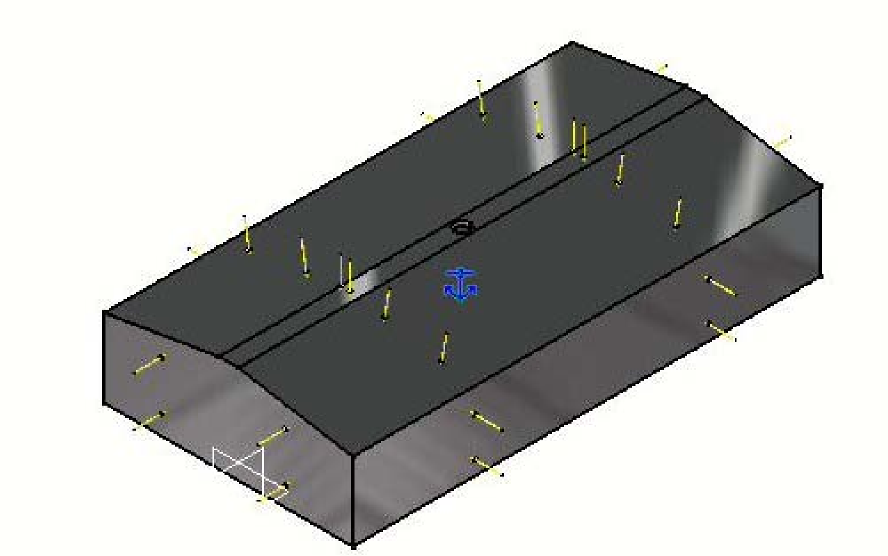


Figure 4.7 CATIA Analysis – Boundary condition

Maximum water depth = 30 m

Maximum pressure, P_{static} = ρgh

$= (1025\ kg/m^3)(9.81ms^{-2})(30m)$

$= 301657.5\ Pa$

$\approx 3\ bar$

Assumption;

1. At the maximum depth, all volume inside the tank filled with water.
2. No pressure different between inside tank and surrounding.

Deformed Mesh

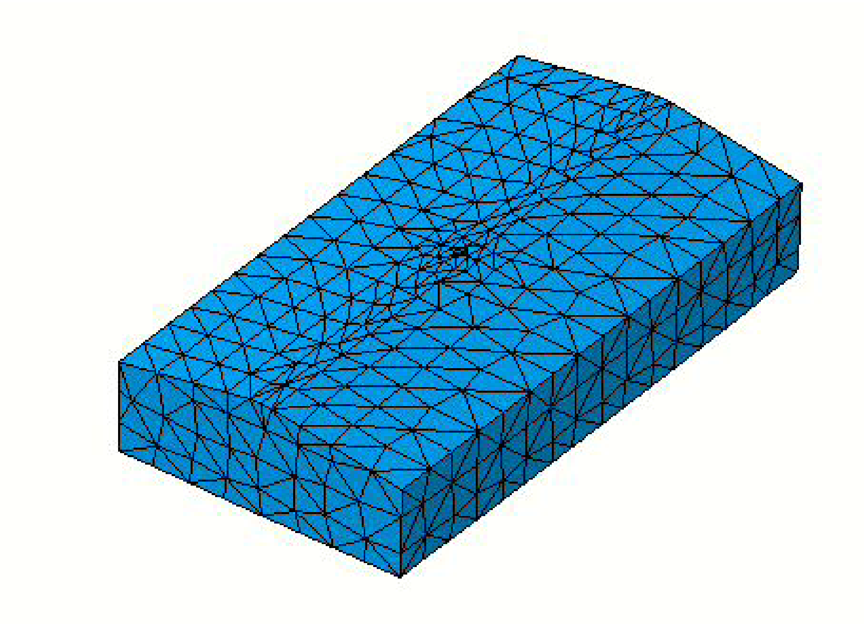


Figure 4.8 CATIA Analysis – Deformed mesh

Stress VonMises Iso Smooth

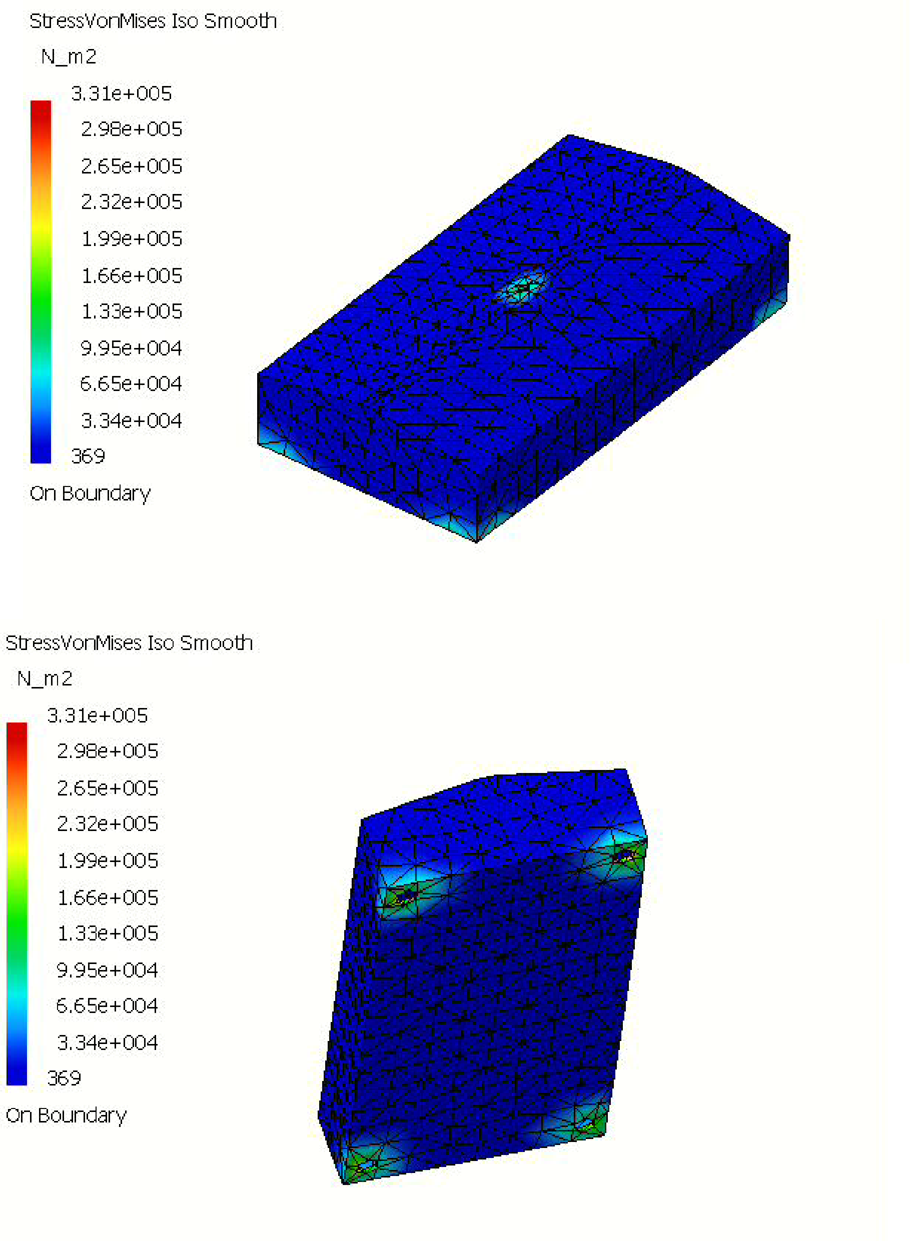


Figure 4.9 CATIA Analysis – StressVonMises Iso Smooth, $P_i = P_0$

From the Analysis1 (above), the original shape of the tank doesn't change as pressure inside and pressure outside the tank is same at 30m below sea level which is approximately 3bar. The selection thickness for the tank meet the requirement of the tank as it is not a pressure vessel.

4.8.3 Drag Force Analysis

The analysis was started by setting the ROV vertical traveling speed, U (during surface) at 1m/s, the density of brine water, $\rho = 1025\ kg/m^3$, the frontal area, $A_D = 0.254m \times 0.4826m = 0.1225m^2$, $C_D \approx 0.8$

$$F_D = 0.5\rho C_D A_D V_O^2$$

$F_D = 0.5\rho C_D A_D V_O^2$

$F_D = 0.5(1025\ kg/m^3)(0.8)(\ 0.1225m^2)(1m/s)^2$

$F_D = 50.225\ kg.m/s^2 = 50.225\ N$

Below was some analysis considered different drag force with different velocity. The analysis was done by using Microsoft Excel software.

Velocity, U (m/s)	Drag Force, F_D (N)
0.00	0.00
0.25	12.56
0.50	25.11
0.75	37.67
1.00	50.23

Table 4.6 Different drag force for different velocity

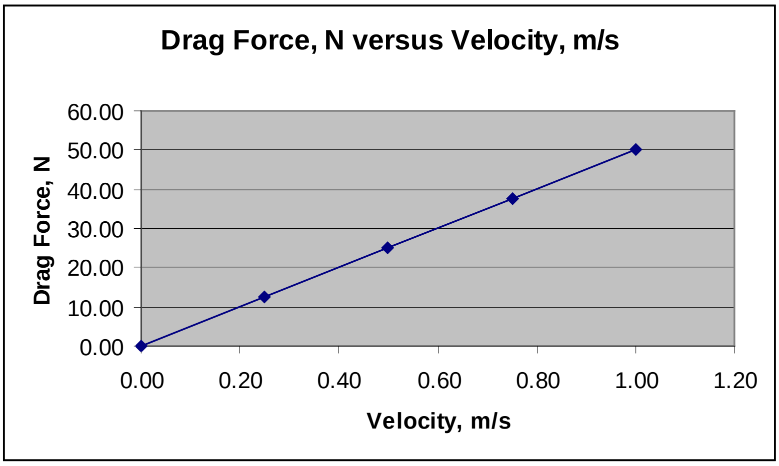


Figure 4.10 Drag Force vs Velocity

4.8.4 Air and Water Flow during submerge and surface

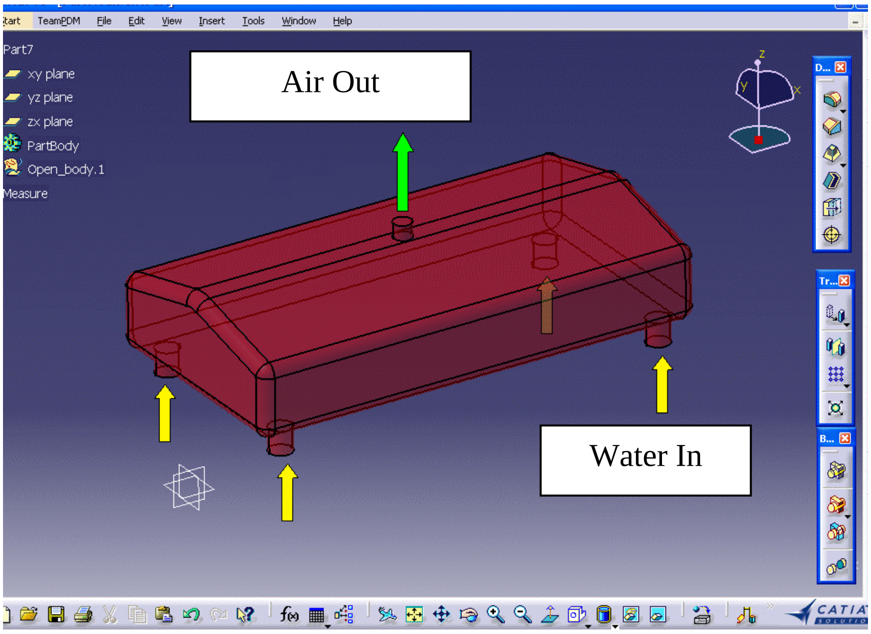


Figure 4.11 Air and water flow during submerge.

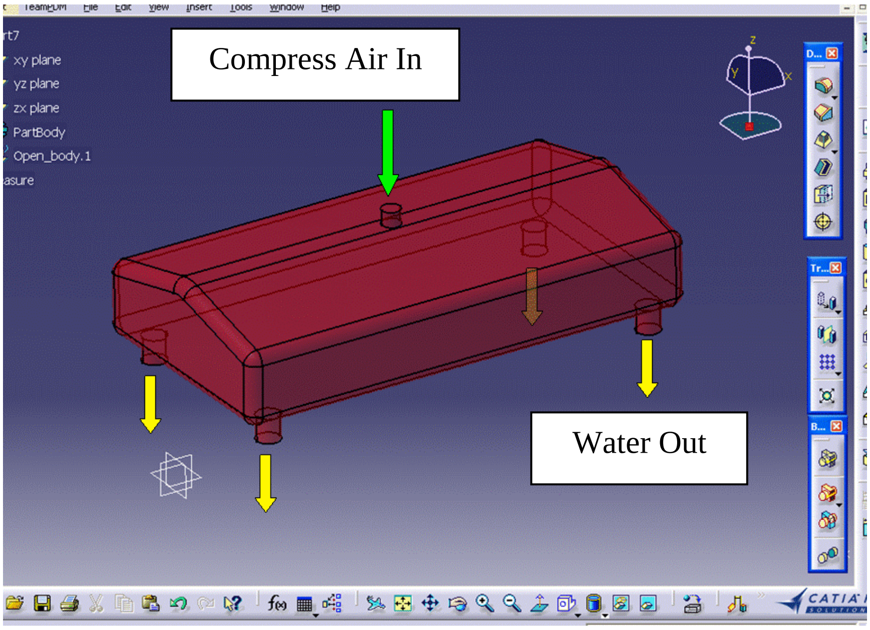


Figure 4.12 Air and water flow during surface

4.9 Pneumatic System

4.9.1 Design consideration

The pneumatic system for this project form an integrated unit several major components. The major parts of the system are the air source, the manifold and the solenoid used as the control system for the buoyancy control Ballast Tank. Because of the air source is a surface tank, the high-strength PVC tubing is used as air lines between the major components

Summary for pneumatic component;

1. Pressurized air tank = air supply source
2. Regulator = lower the pressure to design pressure
3. Manifold & solenoids = control system for the air
4. High-strength PVC tubing = carrying the compressed air

4.9.2 Layout Drawing

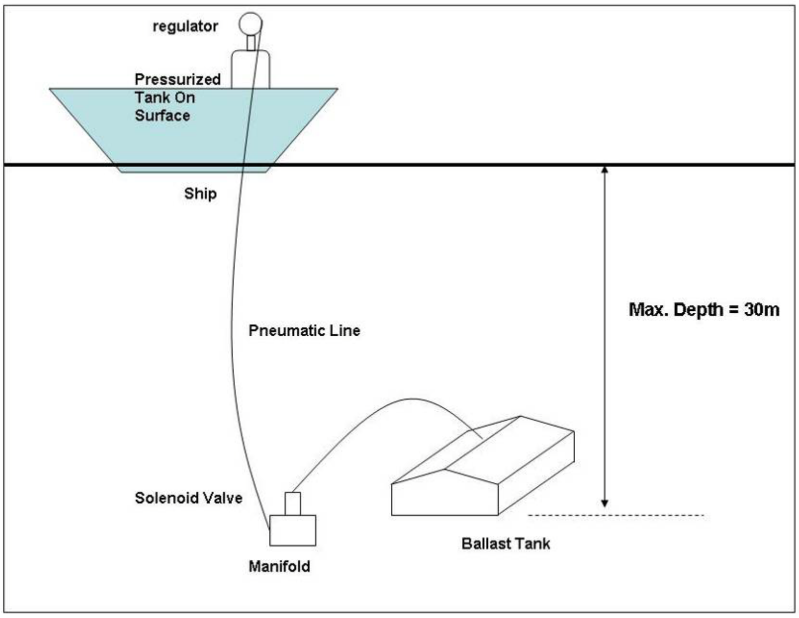


Figure 4.13 Layout drawing of Pneumatic system

4.9.3 Design Justification of Pneumatic system

The air source, a compressed air tank has been selected. The tank is a standard compressed air cylinder which supplies air at a pressure of approximately 3000Psi / 206.84bar. The regulator was used to lower the pressure to design pressure which is 50Psi / 3.5 bars.

The decision to use a compressed air supply above the surface rather than an on board tank was driven in part by space considerations. There is very little spare space inside the ROV. Also, the large surface tank can provide high pressure air for much larger number of cycles of tank filling.

Figure 4.14 Compressed air supply and regulator

There are others alternative rather using the standard compressed air tank which is the removable compressor. But this removable compressor has limitation because it used electricity to operate.

Figure 4.15 Removable air compressors

The surface tank supplies pressurized air to ROV through a tube in the tether, into a manifold and solenoids valve. The manifold and solenoid valve are housed in a main compartment. Air tubes enter and leave through holes drilled through and sealed with silicone sealant.

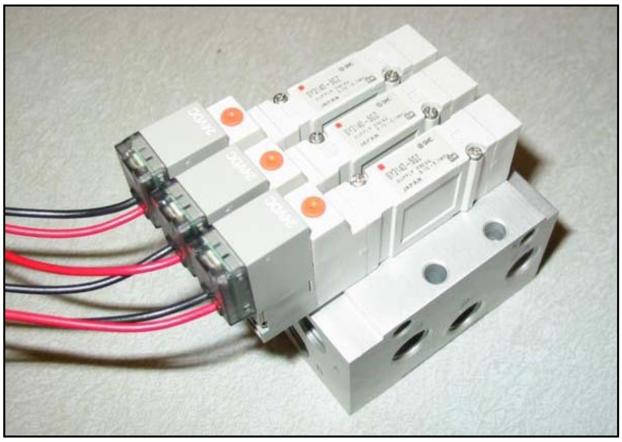


Figure 4.16 Solenoid valve mounted onto the manifold

All the components of the pneumatic system are connected by tubing carrying compressed air. Most of the tubing and fitting in the system correspond to one standard sizing; tube inner diameter 3/16 inch / 4.7625 mm, tube outer diameter ¼ inch / 6.35 mm. The fitting between Ballast Tank and the solenoid valve would be female and male standard fitting.

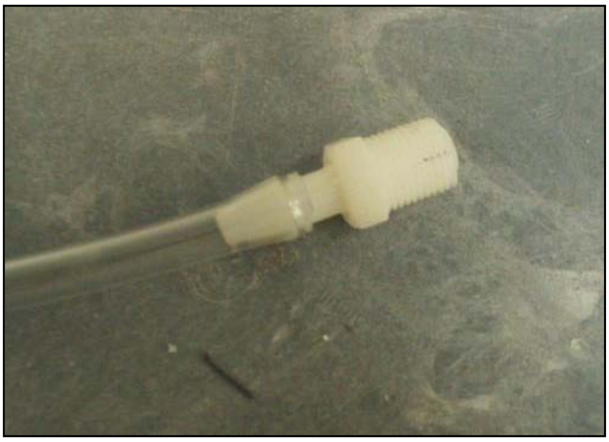


Figure 4.17 Tube and fitting sample

CHAPTER 5

CONCLUSIONS

The focus of this project is on Ballast Tank system to replace vertical thruster in ROV.

The Ballast Tank system was possible to implement in ROV. This system will overcome the difficulty to control the ROV when the vertical thrusters are running continuously. It also provides natural buoyancy force to make sure the ability of the ROV to stay at certain depth.

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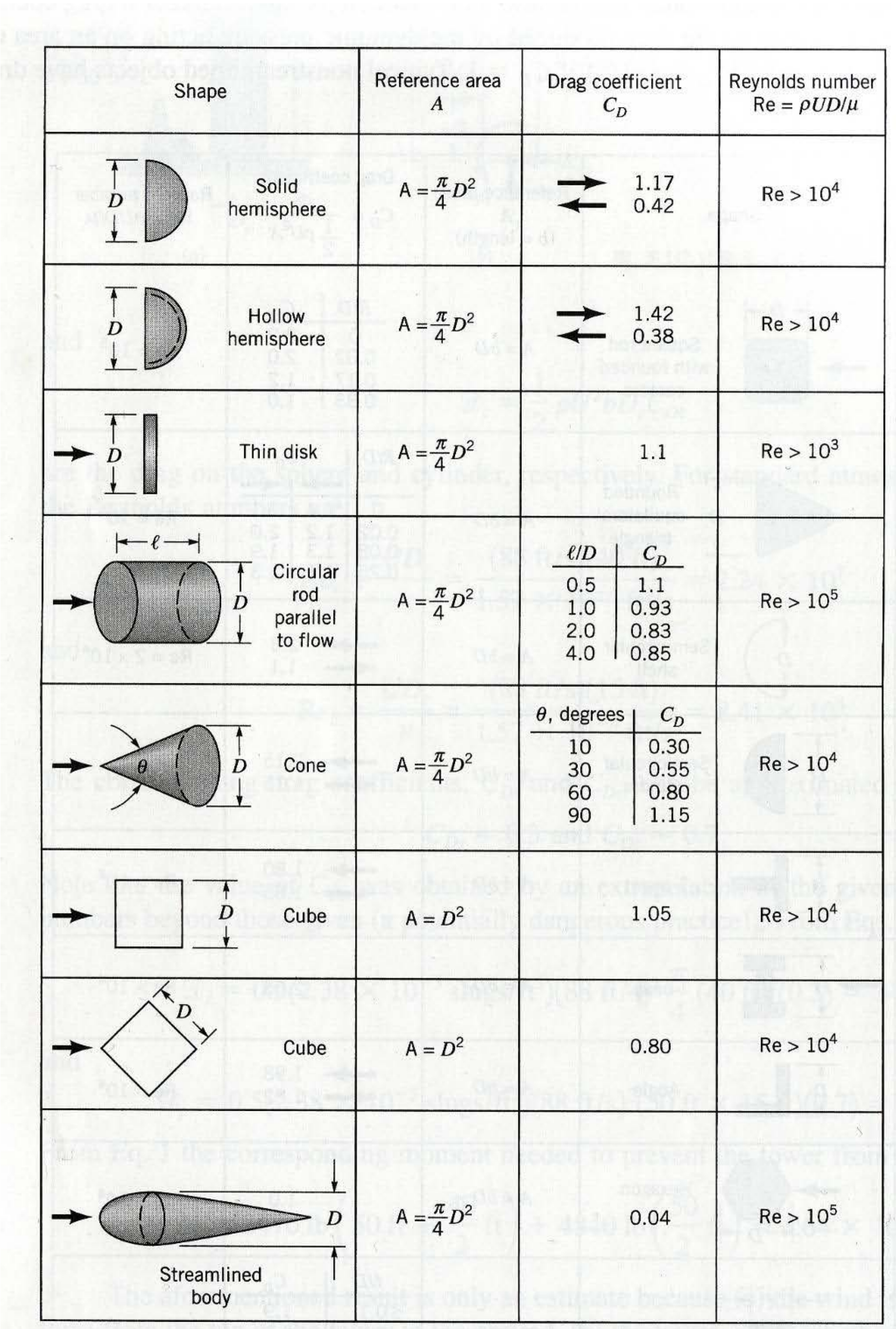
APPENDICES

Shape	Reference area A (b = length)	Drag coefficient $C_D = \dfrac{\mathfrak{D}}{\frac{1}{2}\rho U^2 A}$	Reynold number $Re = \rho UD/\mu$
Square rod with rounded corners	$A = bD$	R/D – C_D: 0 – 2.2; 0.02 – 2.0; 0.17 – 1.2; 0.33 – 1.0	$Re = 10^5$
Rounded equilateral triangle	$A = bD$	R/D – C_D (→ | ←): 0 – 1.4 | 2.1; 0.02 – 1.2 | 2.0; 0.08 – 1.3 | 1.9; 0.25 – 1.1 | 1.3	$Re = 10^5$
Semicircular shell	$A = bD$	→ 2.3; ← 1.1	$Re = 2 \times 10^4$
Semicircular cylinder	$A = bD$	→ 2.15; ← 1.15	$Re > 10^4$
T-beam	$A = bD$	→ 1.80; ← 1.65	$Re > 10^4$
I-beam	$A = bD$	2.05	$Re > 10^4$
Angle	$A = bD$	→ 1.98; ← 1.82	$Re > 10^4$
Hexagon	$A = bD$	1.0	$Re > 10^4$
Rectangle	$A = bD$	ℓ/D – C_D: ≤0.1 – 1.9; 0.5 – 2.5; 0.65 – 2.9; 1.0 – 2.2; 2.0 – 1.6; 3.0 – 1.3	$Re = 10^5$

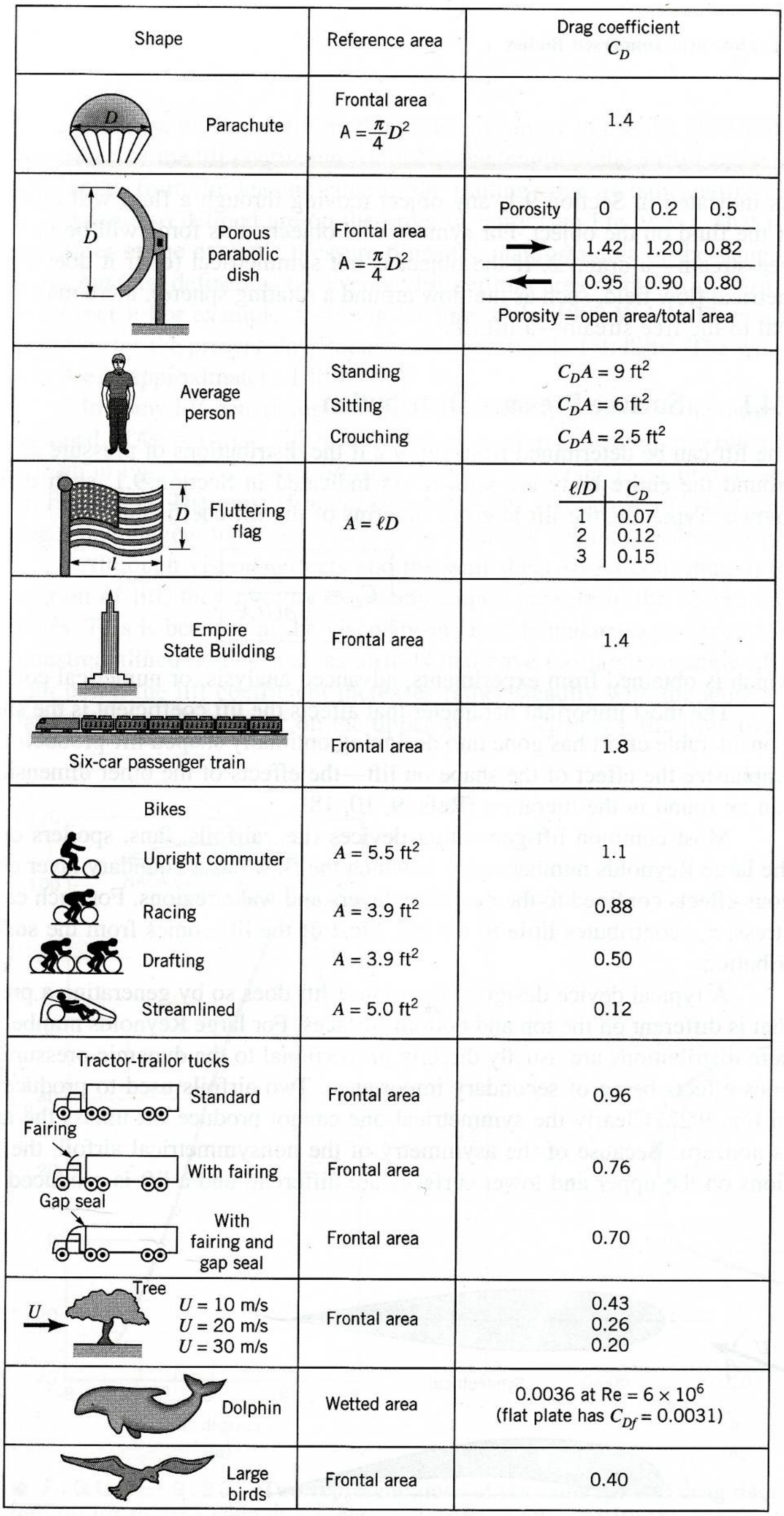
Figure A1 Typical drag coefficients for regular 2D objects [7]

APPENDICES



Shape	Reference area A	Drag coefficient C_D	Reynolds number $Re = \rho UD/\mu$
Solid hemisphere	$A = \frac{\pi}{4}D^2$	→ 1.17 ← 0.42	$Re > 10^4$
Hollow hemisphere	$A = \frac{\pi}{4}D^2$	→ 1.42 ← 0.38	$Re > 10^4$
Thin disk	$A = \frac{\pi}{4}D^2$	1.1	$Re > 10^3$
Circular rod parallel to flow	$A = \frac{\pi}{4}D^2$	ℓ/D : C_D 0.5 : 1.1 1.0 : 0.93 2.0 : 0.83 4.0 : 0.85	$Re > 10^5$
Cone	$A = \frac{\pi}{4}D^2$	θ, degrees : C_D 10 : 0.30 30 : 0.55 60 : 0.80 90 : 1.15	$Re > 10^4$
Cube	$A = D^2$	1.05	$Re > 10^4$
Cube	$A = D^2$	0.80	$Re > 10^4$
Streamlined body	$A = \frac{\pi}{4}D^2$	0.04	$Re > 10^5$

Figure A2 Typical drag coefficients for regular 3D objects



Shape	Reference area	Drag coefficient C_D
Parachute	Frontal area $A = \frac{\pi}{4}D^2$	1.4
Porous parabolic dish	Frontal area $A = \frac{\pi}{4}D^2$	Porosity: 0, 0.2, 0.5; → 1.42, 1.20, 0.82; ← 0.95, 0.90, 0.80; Porosity = open area/total area
Average person	Standing Sitting Crouching	$C_DA = 9$ ft^2 $C_DA = 6$ ft^2 $C_DA = 2.5$ ft^2
Fluttering flag	$A = \ell D$	ℓ/D: 1, 2, 3; C_D: 0.07, 0.12, 0.15
Empire State Building	Frontal area	1.4
Six-car passenger train	Frontal area	1.8
Bikes		
Upright commuter	$A = 5.5$ ft^2	1.1
Racing	$A = 3.9$ ft^2	0.88
Drafting	$A = 3.9$ ft^2	0.50
Streamlined	$A = 5.0$ ft^2	0.12
Tractor-trailor tucks		
Standard	Frontal area	0.96
Fairing: With fairing	Frontal area	0.76
Gap seal: With fairing and gap seal	Frontal area	0.70
Tree: $U = 10$ m/s $U = 20$ m/s $U = 30$ m/s	Frontal area	0.43 0.26 0.20
Dolphin	Wetted area	0.0036 at Re = 6×10^6 (flat plate has $C_{Df} = 0.0031$)
Large birds	Frontal area	0.40

Figure A3 Typical drag coefficients for objects of interest[7]

APPENDICES

Material	Modulus of elasticity, E		Modulus of rifidity, G		Poisson's Ratio	Unit weight		
	Mpsi	Gpa	Mpsi	Gpa		lb/in3	lb/ft3	kN/m3
Aluminum (all alloys)	10.3	71.0	3.8	26.2	0.334	0.098	169	26.6
Beryllium copper	18.0	124.0	7.0	48.3	0.285	0.297	513	80.6
Brass	15.4	106.0	5.82	40.1	0.324	0.309	534	83.8
Carbon steel	30.0	207.0	11.5	79.3	0.292	0.282	487	76.5
Cast iron, gray	14.5	100.0	6.0	41.4	0.211	0.260	450	70.6
Copper	17.2	119.0	6.49	44.7	0.326	0.322	556	87.3
Douglas fir	1.6	11.0	0.6	4.1	0.33	0.016	28	4.3
Glass	6.7	46.2	2.7	18.6	0.245	0.094	162	25.4
Incomel	31.0	214.0	11.0	75.8	0.29	0.307	530	83.3
Lead	5.3	36.5	1.9	13.1	0.425	0.411	710	111.5
Magnesium	6.5	44.8	2.4	16.5	0.35	0.065	112	17.6
Molybdenum	48.0	331.0	17.0	117.0	0.307	0.368	636	100.0
Monel metal	26.0	179.0	9.5	65.5	0.32	0.319	551	86.6
Nickel silver	18.5	127.0	7.0	48.3	0.322	0.316	546	85.8
Nickel steel	30.0	207.0	11.5	79.3	0.291	0.280	484	76.0
Phospfor broze	16.1	111.0	6.0	41.4	0.349	0.295	510	80.1
Stainless steel (18-8)	27.6	190.0	10.6	73.1	0.305	0.280	484	76.0

Table A1 Physical constant of materials[9]

APPENDICES – Example of CATIA analysis

1. Selection thickness = 3.175 mm (meet the requirement)

MESH:

Entity	Size
Nodes	954
Elements	2964

ELEMENT TYPE:

Connectivity	Statistics
TE4	2964 (100.00%)

ELEMENT QUALITY:

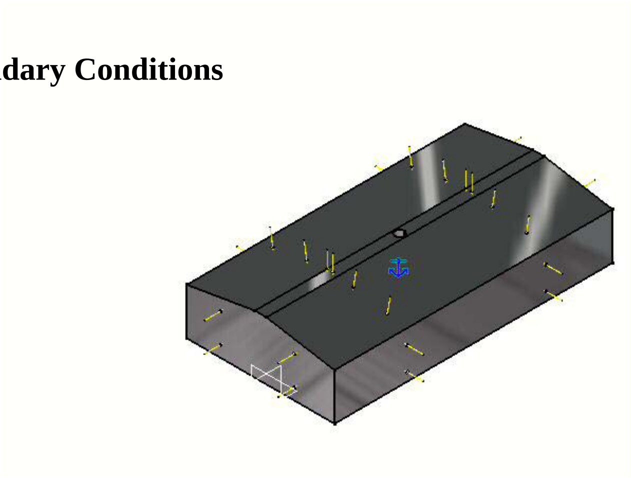
Criterion	Good	Poor	Bad	Worst	Average
Skewness	2713 (91.53%)	241 (8.13%)	10 (0.34%)	0.961	0.533
Jacobian	2964 (100.00%)	0 (0.00%)	0 (0.00%)	1.000	1.000
Stretch	2963 (99.97%)	1 (0.03%)	0 (0.00%)	0.295	0.562
Min. Length	2964 (100.00%)	0 (0.00%)	0 (0.00%)	6.043	17.470
Max. Length	2964 (100.00%)	0 (0.00%)	0 (0.00%)	54.630	38.517
Shape Factor	2964 (100.00%)	0 (0.00%)	0 (0.00%)	0.309	0.596
Length Ratio	2964 (100.00%)	0 (0.00%)	0 (0.00%)	4.918	2.354

Properties.1

Material	Young Modulus	Poisson Ratio
Aluminium.1.1 : Alloy 1100-H14 (99 % Al)	7e+010N_m2	0.346

STATIC CASE

Boundary Conditions



STRUCTURE Computation

Number of nodes : 954
Number of elements : 2964
Number of D.O.F. : 2862
Number of Contact Elements : 0
Number of Kinematic relations : 0

RESTRAINT Computation

Name: RestraintSet.1

Number of S.P.C : 6

LOAD Computation

Name: LoadSet.1

Applied load resultant :

Fx = -1 . 173e-012 N
Fy = -5 . 258e-013 N
Fz = 7 . 698e+000 N
Mx = -1 . 161e+000 Nxm
My = 5 . 519e+000 Nxm
Mz = 5 . 258e-013 Nxm

STIFFNESS Computation

Number of lines	: 2862
Number of coefficients	: 49158
Number of blocks	: 1
Maximum number of coefficients per bloc	: 49158
Total matrix size	: 0 . 57 Mb

SINGULARITY Computation

Restraint: RestraintSet.1

Number of local singularities	: 0
Number of singularities in translation	: 0
Number of singularities in rotation	: 0
Generated constraint type	: MPC

CONSTRAINT Computation

Restraint: RestraintSet.1

Number of constraints	: 6
Number of factorized constraints	: 6
Number of deferred constraints	: 0

NUMBERING Computation

Restraint: RestraintSet.1

Numbering Method	: SLOAN
Number of connected nodes	: 954
Nodal maximum front width	: 62
Nodal maximum band width	: 205

FACTORIZED Computation

Method	:	SPARSE
Number of factorized degrees	:	2856
Number of supernodes	:	541
Number of overhead indices	:	21744
Number of coefficients	:	243430
Maximum front width	:	255
Maximum front size	:	32640
Size of the factorized matrix (Mb)	:	1 . 85722
Number of blocks	:	1
Number of Mflops for factorization	:	3 . 398e+001
Number of Mflops for solve	:	9 . 766e-001
Minimum relative pivot	:	8 . 069e-003

DIRECT METHOD Computation

Name: StaticSet.1

Restraint: RestraintSet.1

Load: LoadSet.1

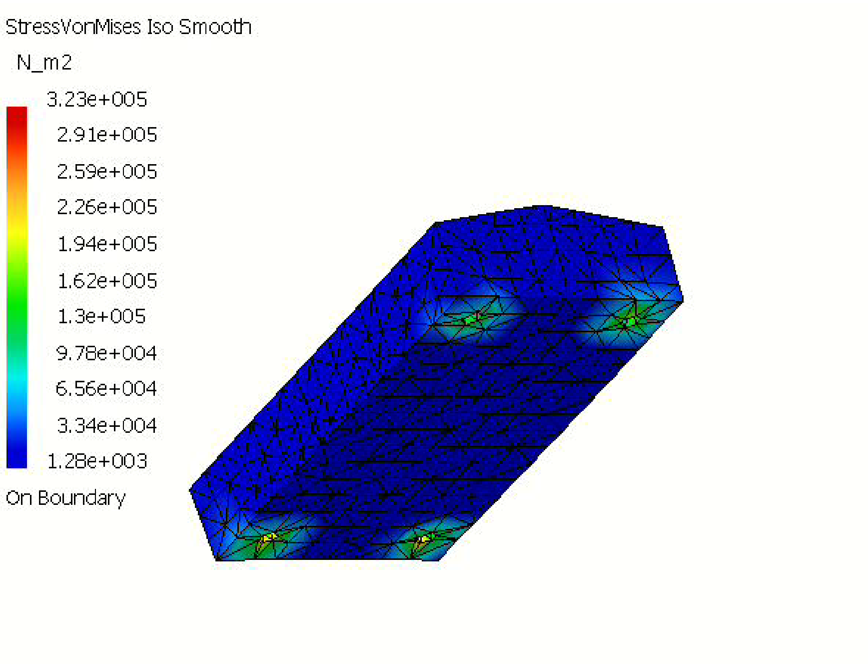
Strain Energy : 3.709e-003 J

Equilibrium

Components	Applied Forces	Reactions	Residual	Relative Magnitude Error
Fx (N)	-1.1726e-012	6.1959e-012	5.0233e-012	1.1336e-014
Fy (N)	-5.2580e-013	5.4143e-011	5.3618e-011	1.2100e-013
Fz (N)	7.6983e+000	-7.6983e+000	1.7508e-011	3.9511e-014
Mx (Nxm)	-1.1615e+000	1.1615e+000	-5.0198e-012	2.3601e-014
My (Nxm)	5.5193e+000	-5.5193e+000	7.7005e-012	3.6204e-014
Mz (Nxm)	5.2580e-013	-1.8995e-011	-1.8470e-011	8.6836e-014

Deformed Mesh

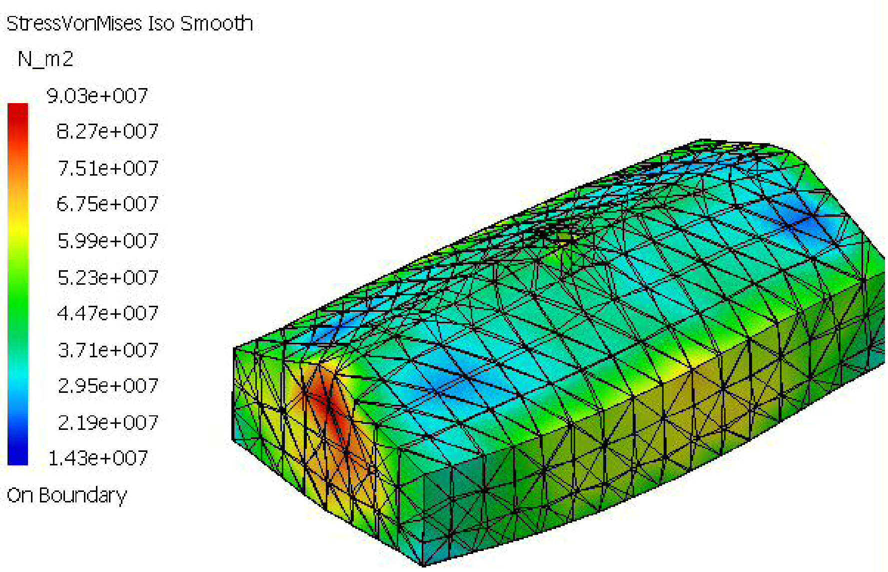
StressVonMises Iso Smooth

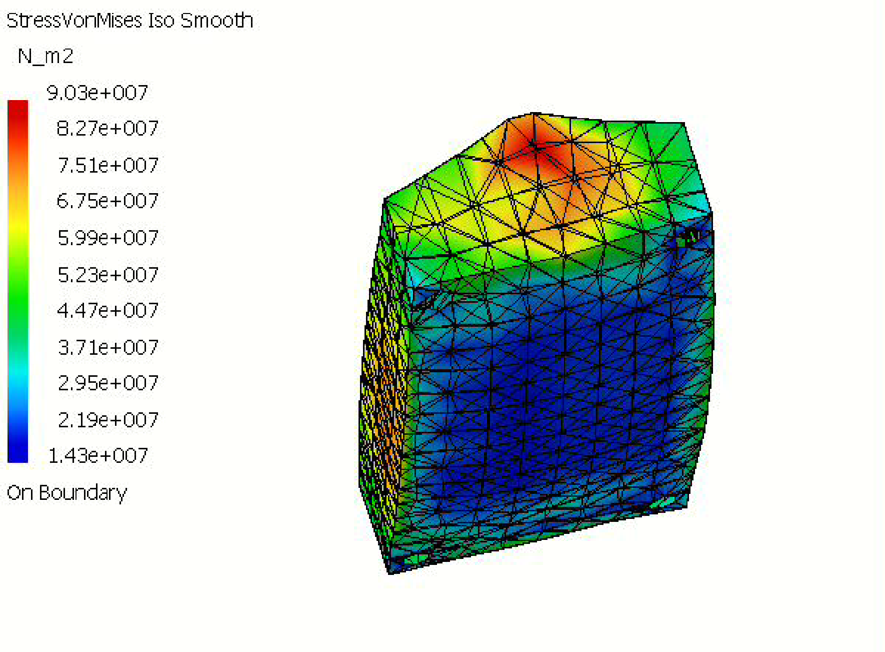


APPENDICES – Example of CATIA analysis

2. Thickness = 0.04 mm (not meet the requirement)

Even thought the outside and inside pressure are at equilibrium (no pressure different), but there will be some effect on the tank during surface activity (compress air into the tank) because of the thickness. Below is the not acceptance thickness during analysis.





Detail drawing of ROV Chassis

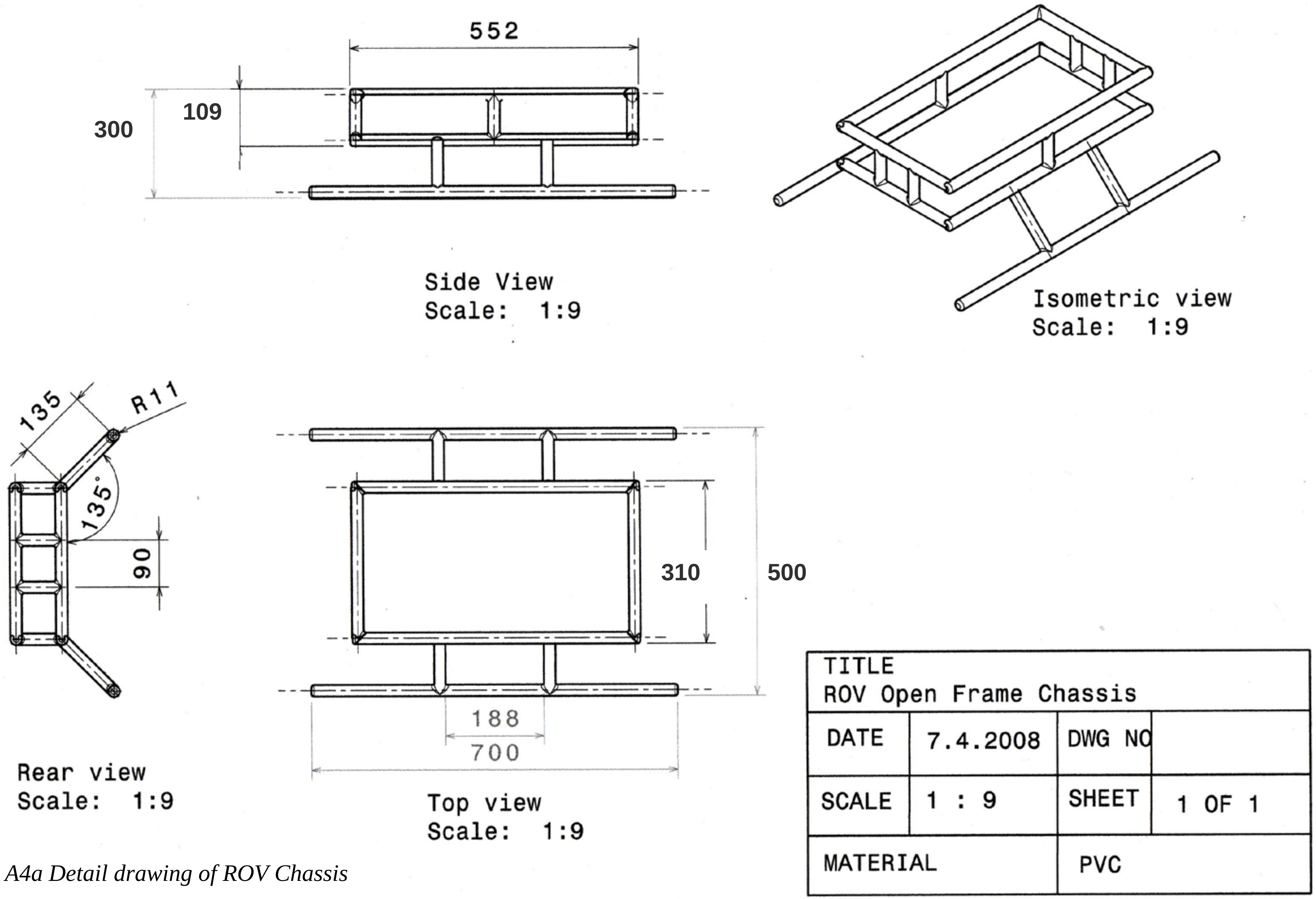
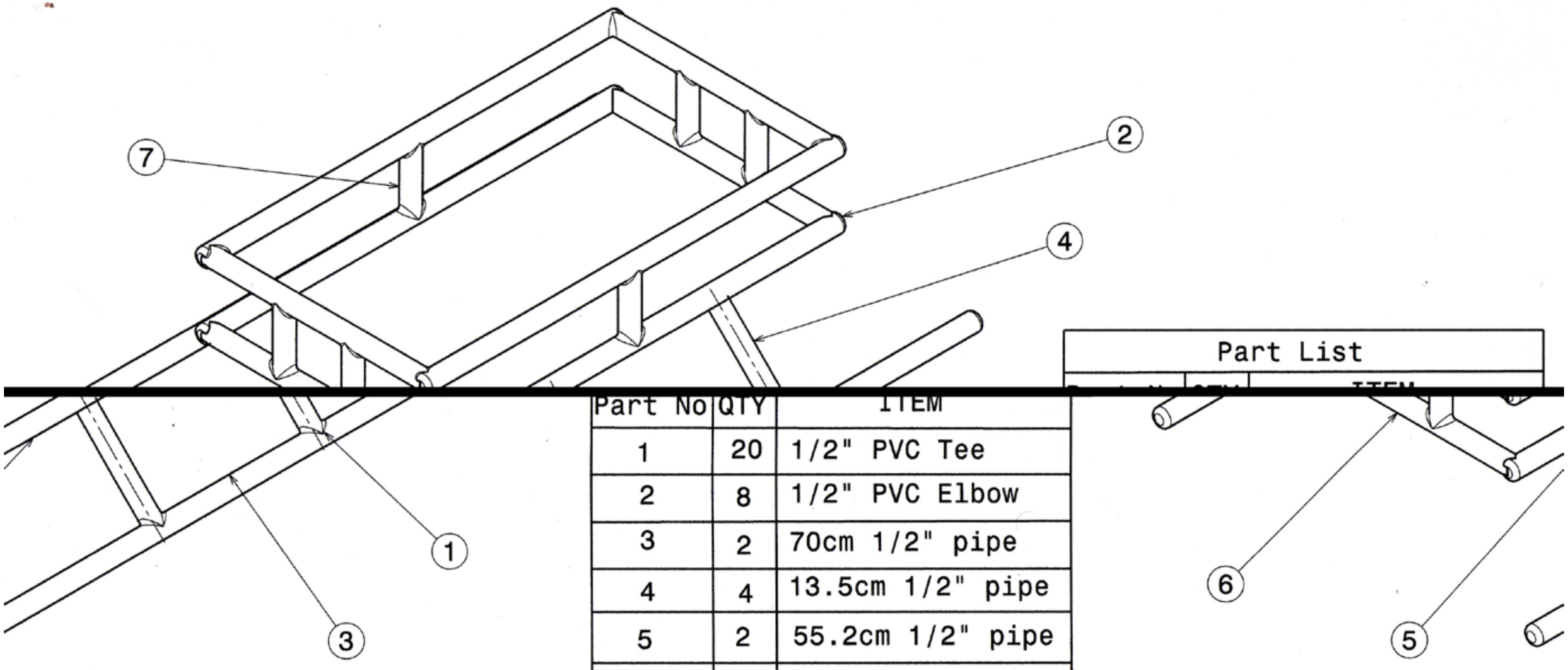


Figure A4a Detail drawing of ROV Chassis

Assembly Drawing of ROV Chassis



Part List

Part No	QTY	ITEM
1	20	1/2" PVC Tee
2	8	1/2" PVC Elbow
3	2	70cm 1/2" pipe
4	4	13.5cm 1/2" pipe
5	2	55.2cm 1/2" pipe
6	2	25.4cm 1/2" pipe
7	6	10.9cm 1/2" pipe

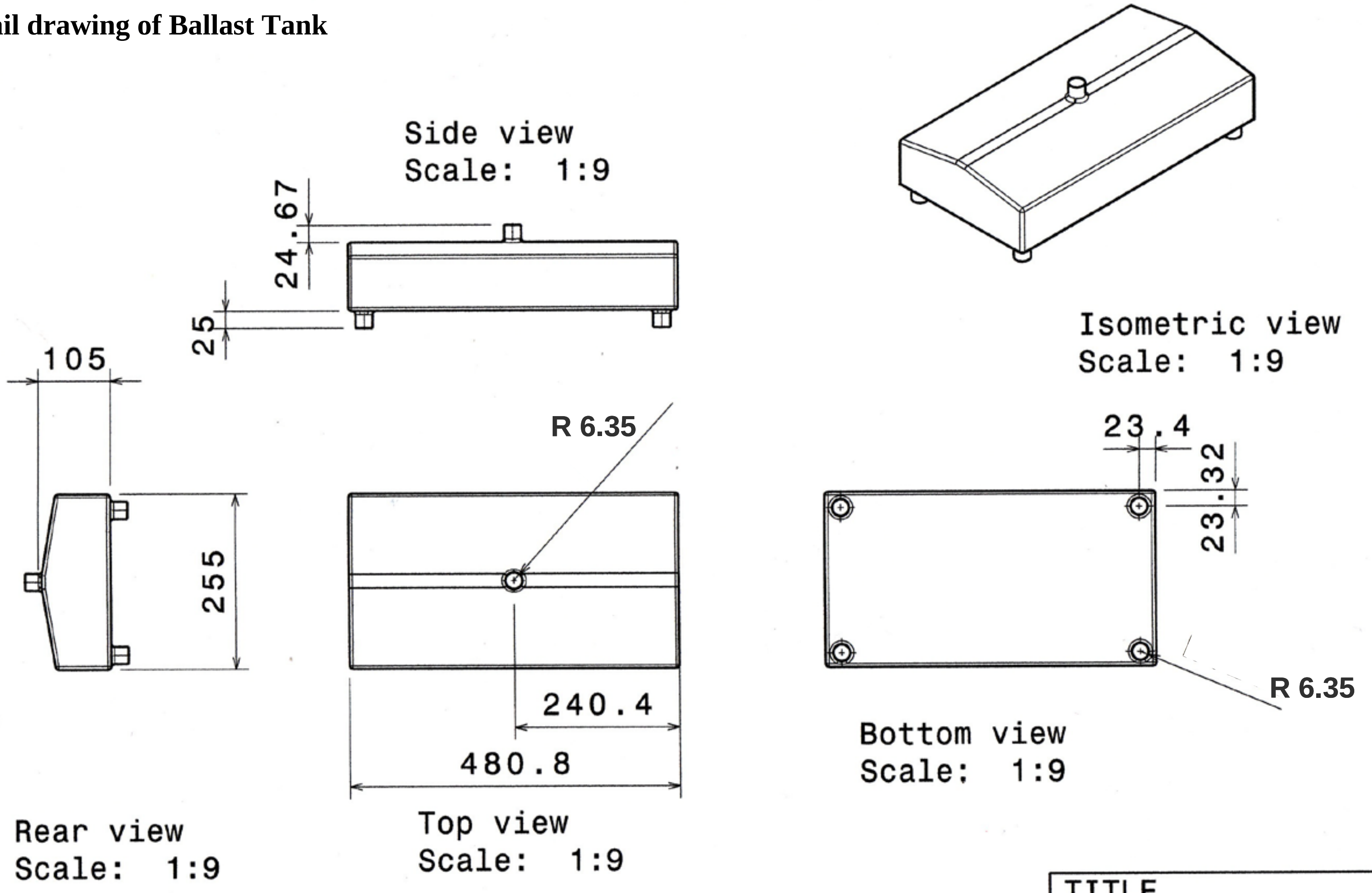
TITLE
ROV Open Frame Chassis

7.4.2008	DWG NO	
1 : 5	SHEET	1 OF 1

DATE
SCALE

Figure A4b Assembly drawing of ROV Chassis

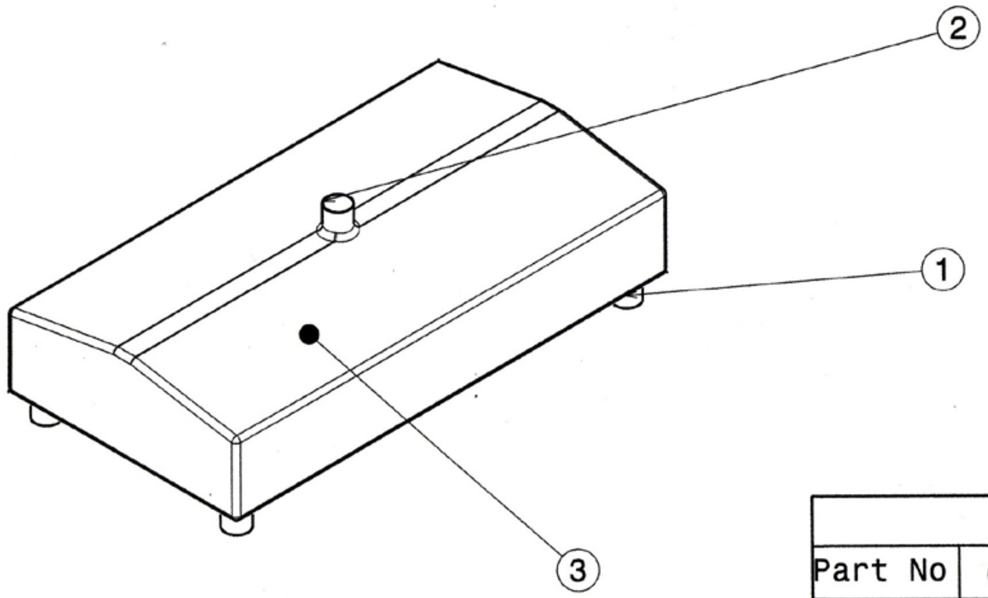
Detail drawing of Ballast Tank



TITLE ROV Ballast Tank			
DATE	7.4.2008	DWG NO	
SCALE	1 : 9	SHEET	1 OF 1
MATERIAL		Aluminium	

Figure A5a Detail drawing of Ballast Tank

Assembly Drawing of Ballast Tank



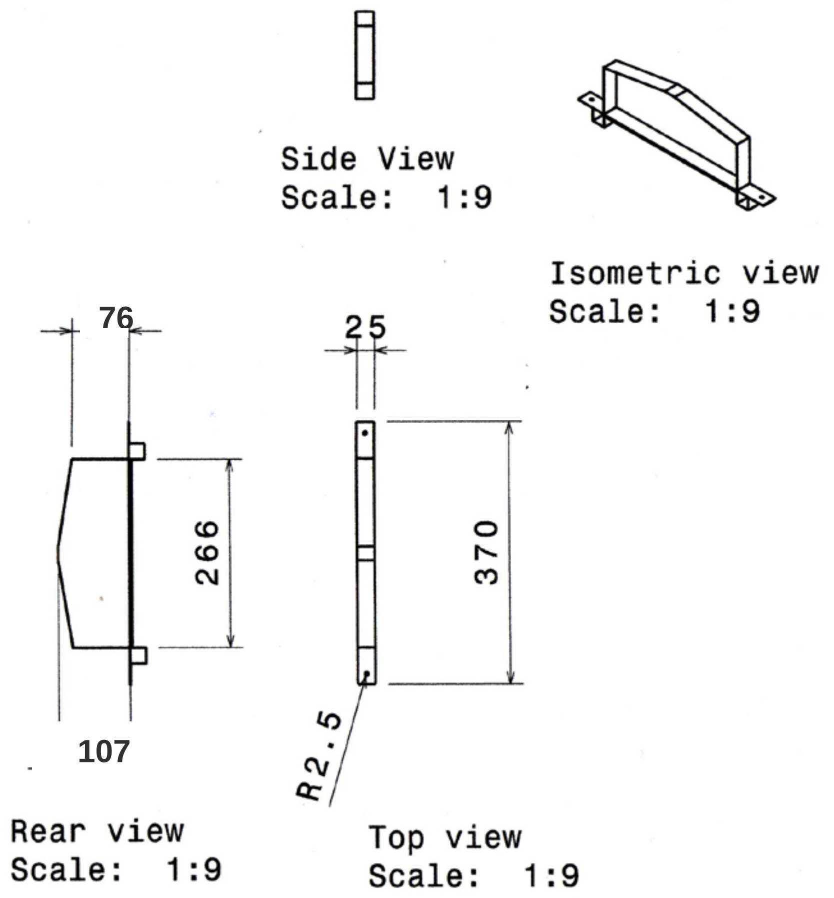
Isometric view
Scale: 1:5

Part List		
Part No	QTY	ITEM
1	4	1/2"water inlet/outlet
2	1	1/2" Air inlet/outlet
3	1	Ballast tank

TITLE ROV Ballast Tank			
DATE	7.4.2008	DWG NO	
SCALE	1 : 5	SHEET	1 OF 1

Figure A5b Assembly drawing of Ballast Tank

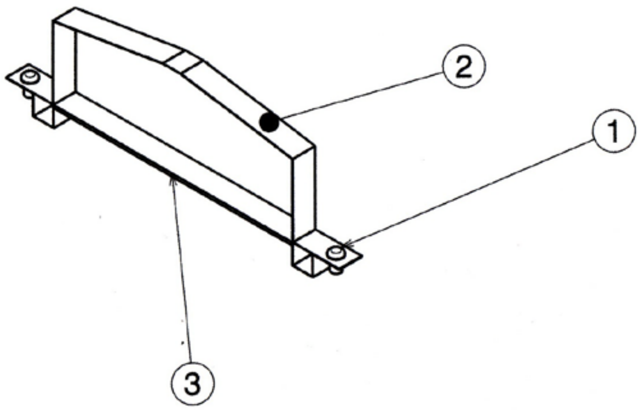
Detail Drawing of Bracket



TITLE ROV Ballast Tank Bracket			
DATE	7.4.2008	DWG NO	
SCALE	1 : 9	SHEET	1 OF 1
MATERIAL		Aluminium	

Figure A6a Detail drawing of bracket

Assembly Drawing of Bracket



Isometric view
Scale: 1:5

Part List		
Part No	QTY	ITEM
1	2x2	Slotted panhead skrew
2	1x2	Top side of bracket
3	1x2	Bottom side of brecket

TITLE ROV Ballast Tank Bracket			
DATE	7.4.2008	DWG NO	
SCALE	1 : 5	SHEET	1 OF 1

Figure A6b Assembly drawing of bracket